Impacts of market economy access and livelihood conditions on agro-food transition in rural communities in three macro-regions of Brazil

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Abstract

Urbanization has threatened rural communities' livelihoods worldwide, changing their agro-food systems from locally produced traditional items to industrialized foodstuffs. The main objective was to investigate the relationship between livelihood conditions and the agro-food transition process in rural communities of the Center-West, Northeast, and Amazon regions of Brazil. We hypothesized that traditional agroecosystems and local food habits changed with greater access to market economies. The study was conducted with semi-structured questionnaire interviews to verify agro-food patterns, subsistence farming, natural resource use, and socioeconomic conditions. Moreover, we used stable isotope ratios from the inhabitants' fingernails to determine the food source and trophic chain diversity. Data from questionnaires were analyzed using a Bayesian clustering model to characterize the socioeconomic conditions and agro-food patterns among rural and urban communities. The isotopic data were appraised through a nonparametric model to assess food differences among Brazilian regions and different community types. The Bayesian model allowed us to determine the optimal number of groups according to descriptive socioeconomic and agro-food variables sorted by each specific location. We also verified a food change from C_3 (more natural) to C_4 (more processed) with an increase in $\delta^{13}C$ and a decrease in $\delta^{15}N$ in the city and town localities. This indicates a livelihood shift from locally produced foods to processed items toward urban areas. Although remote villages showed more maintenance of their agro-food systems, increased access to market economies and the supermarket diet is changing the livelihood conditions of rural communities, which can compromise their traditional farming and food sovereignty.

Keywords Livelihood · Rural communities · Food sovereignty · Stable isotopes

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1 Introduction

Urbanization and market economy integration has changed the countryside's livelihood activities, making food sovereignty a common dilemma in rural areas (Piperata et al., 2011; Hanazaki, 2012). Besides nutritional consequences, this socioeconomic development is associated with the food transition process, which has replaced local agricultural production and traditional crop items with the consumption of highly processed foodstuffs, such as sweets, dairy products, and sausages (Jesus Silva, 2017; Nardoto, 2011).

One of the main problems of this replacement of food habits, known as nutritional transition, is the association with a rise in chronic diseases related to diet, including diabetes, coronary disease, stroke, and cancer (Popkin, 2006). In remote rural communities, the transition can result in the macro-transformation pattern of food habits and livelihood conditions, disconnecting people from their local biocultural universe, mainly through modern food production and increased urban access (Jesus Silva, 2019; Piperata et al., 2016; Poulain, 2017; Schor & Azenha, 2017). Besides nutritional effects, the disconnection in remote areas could impact food sovereignty maintenance and even the minimum nutrition necessary for survival (Dutra, 2018).

According to Gazolla and Schneider (2007), this transformation process can lead farmers to change their production strategies to highly specific production systems, such as soy, corn, coffee, and losing their rights over food sovereignty. Therefore, understanding the relationship between livelihood conditions and the agro-food transition in the multiple rural communities surveyed will be very important to assess the level of maintenance of food customs and autonomy concerning subsistence production and, consequently, determine which factors are more associated with the change process.

The main factors influencing the gradual replacement of local items by processed foods are greater access to supermarkets and urban areas, increased income from government assistance, and broader participation in the paid labor market (Jesus Silva et al., 2017, 2019; Nardoto et al., 2011; Piperata et al., 2011). Although Schor and Azenha (2017) say that few studies examine the impact of these factors on food habits and the livelihood of rural communities, there has been increased research in this field (Brondizio, 2008; Godoy, 2007; Jesus Silva et al., 2017; Nardoto et al., 2011).

Some have addressed the transition process in rural communities from an environmental perspective (Brondizio, 2008; Godoy et al., 2007), while Murrieta and Dufour (2004) have focused on food anthropology. Others have focused on the socioeconomic perspective of changes in livelihood activities (Dou, 2017; Ellis & Bahiigwa, 2003; Nguyen, 2015). However, few studies have considered this issue on a larger scale with different ethnic groups such as riverine people, artisanal fishers, slave remnants, and rural settlements. Even fewer have approached the subject in an interdisciplinary and pragmatic way, such as using socioeconomic and livelihood surveys jointly with stable isotopes to assess agro-food patterns.

Nardoto et al. (2011) were the first to detect nutritional transition through carbon and nitrogen stable isotopes in the Brazilian Amazon region. Reinaldo et al. (2015) applied the same methodology to verify food changes in rural communities in Brazil's Northeast region. Jesus Silva et al. (2017) were pioneers in approaching the subject through multinomial logistic regression analyses of semi-structured questionnaire data to assess the relative influence of socioeconomic and environmental factors on local food habits. Recently, two relevant articles have been published on food transition in Brazil: one with this joint methodology but restricted to a specific slave-remnant rural community called *Kalunga* located in the Center-West region (Jesus Silva et al., 2019) and the other with an isotopic mapping

of fingernail composition in several rural communities in the Amazon, Center-West, and Northeast regions (Nardoto, 2020).

No studies have used Bayesian models to analyze the field questionnaire dataset combined with stable isotopes to determine agro-food patterns. Stable isotopes are variations of a chemical element with different atomic masses and are used to infer the types of foods consumed after some time (Farquhar et al., 1989). However, this biochemistry tool does not provide details about individual agro-food items. These details are assessed through the livelihood and food questionnaires applied in the field (Jesus Silva et al., 2019; Nardoto et al., 2011). The application of Bayesian models aims to improve the appraisals of the questionnaires and, in cross-checking with the isotopic composition data of fingernails, reveal more details about the transition pattern between urban and rural areas.

We previously found a more homogeneous food habit based on plants that follow the C_4 photosynthetic metabolism (sugarcane, maize, and grasses) in urban areas (Jesus Silva et al. 2019; Nardoto et al., 2011, 2020). In general, while the $\delta^{13}C$ values in C_4 plants vary from -11 to -15‰ , in C_3 plants, they range from -24 to -38‰ (Farquhar et al. 1989). Though few plants follow the C_4 photosynthetic type (e.g., maize, sugarcane, and tropical grasses), they highly influence human diets, since maize and sugarcane are staple ration foods of cattle, pork, goats, and chicken (Jesus Silva et al., 2019; Nardoto et al., 2011).

Usually, there is higher consumption of foodstuffs derived from C_3 plants such as cassava flour, rice, and beans in rural areas. Local food items such as manioc (*Manihot esculenta*), fish, and game meat are important as sources of protein and energy in rural Brazilian communities (Carneiro, 2003; Murrieta & Dufour, 2004; Padoch et al., 2008). Isotopically, manioc is a C_3 photosynthetic plant type with $\delta^{13}C$ varying from -25 to -29‰ (Nardoto et al., 2011).

Furthermore, the most crucial carbon sources for freshwater fish and game also have a C_3 -like origin, comprising items such as leaves, fruits, phytoplankton and zooplankton, seeds, plant debris, or other animals that also have a C_3 -based diet (Nardoto et al., 2011; Oliveira, 2006). Since the $\delta^{13}C$ value indicates the primary food source (C_3 , which is more natural, or C_4 , which is more processed), the $\delta^{15}N$ value generally points out animal protein consumption levels (Huelsemann, 2009). Usually, the $\delta^{15}N$ value increases by around 3‰ at each step of the food chain (Nardoto et al., 2011).

In this context, we expected a less negative signal of $\delta^{13}C$ and lower of $\delta^{15}N$ in urban areas (city, coast, and towns), whereas the opposite is expected in remote rural locations (villages and islands). A set of factors usually present in remote sites, such as limited market access and sociocultural and environmental principles, tend to decrease the food intake of C_4 plants and increase game meat and freshwater fish consumption with higher $\delta^{15}N$ values (Lima et al., 2019). Additionally, we hope to identify the main agro-food patterns through Bayesian models and cluster them according to socioeconomic and livelihood conditions over different regions.

Therefore, the main objective of this study was to explore the “Bayesian” relationship between livelihood conditions and the agro-food transition process in rural communities of Brazil’s three macro-regions. An additional objective was to evaluate agro-food pattern differences between rural and urban areas through the isotopic composition ($\delta^{13}C$ and $\delta^{15}N$) of fingernails, assuming that the traditional agroecosystems and local food habits changed with greater access to market economies. The central hypothesis is that sites with better livelihood conditions and more readily accessible market economies will be going through a higher transition process with less game meat, fishing, subsistence farming, and more chicken and processed foodstuffs from C_4 plants.

2 Materials and methods

2.1 Study area and sampling

This study was carried out almost on the same geographical scale as Nardoto et al. (2020) in household units (HU) from three macro-regions of Brazil (Amazon, Center-West, and Northeast) distributed along 15 counties, with 19 specific sites (Table 1) with at least one adult (i.e., ≥ 18 years) of each HU. Sampling was performed randomly, considering the availability for interviews and if the dwelling was inhabited.

The field survey was conducted in the western and eastern Amazon regions, mainly among riverine people located along the Solimões–Amazon River in the Brazilian states of Amazonas (AM) and Pará (PA). The most remote communities on the Amazon scale were the riverine village of Caxiuanã National Forest and the artisanal fishermen of Apeú Salvador Island, both in PA. In the Centre-West region, we conducted a study among inhabitants of counties situated in the microregion of Chapada dos Veadeiros and into the Cerrado biome, which possesses a type of rocky vegetation with a distinct phytophysognomy called “*cerrado rupestre*” (Jesus Silva et al., 2019).

Finally, in the Northeast region, sampling was carried out in fishing villages of the Ponta do Tubarão Sustainable Development Reserve and in rural communities from the two largest counties of the State of Rio Grande do Norte (RN). We sorted the database and fingernail samples according to the type of source region and accessibility to urban areas,

Table 1 Number of respondents and fingernails collected from each locality sampled in Brazil

Localization			Inhabitants	Interviews(n)	Region
Name	Site	Environment			
Alvarães	Town	Floodplain	15,546	45	Western Amazon—AM
Benjamin Constant	Town	Mainland	43,935	30	
Tefé	City		62,662	54	
Uarini	Town	Floodplain	13,690	17	Eastern Amazon—PA
Tabatinga	Town	Mainland	65,884	29	
Caxiuanã/Melgaço	Village	Floodplain	2615	29	
Apeú Salvador/Viseu	Island	Sandbank	1907	39	
Mossoró	City	Caatinga	237,8241	82	Northeast—RN
	Town			95	
Macau	Coast	Zona da Mata	31,584	36	Center-West—GO
	Town			33	
Natal	City		803.739	96	
Guamaré	Town		14,875	30	
Cavalcante	Town	Cerrado	9875	8	
	Village			14	
Teresina	Town		2733	35	
Monte Alegre	Village		8116	23	
Alto Paraíso	City		6638	24	
	Town			17	

AM Amazonas; PA Pará; RN Rio Grande do Norte; GO Goiás

such as city, town, village, coast, and island. General sample units can be seen with more details in Nardoto et al. (2020), whereas Jesus Silva et al. (2019) demonstrate site-specific details for *Kalunga* villages.

2.2 Data collection and analysis

Data were collected through semi-structured questionnaire interviews with closed- and open-ended questions on livelihood, socioeconomic conditions, subsistence farming, hunting, gathering, and food habits, such as demographic aspects and market participation. The interview script followed the same simple questions as those from Jesus Silva et al. (2019) and was applied in a single instance over 30 days, excluding Sundays. A list of the most consumed foods in Brazil was used, with adjustments for specific regions, to record the items that often comprised the local staple food.

The interviews were conducted without replication at each location, mainly due to difficulties accessing certain areas and limited availability of financial resources to cover all field samples. In this sense, any possible bias in data obtained from the questionnaires was overcome through the isotopic composition analysis of fingernail samples collected from each interviewee, which reflected their food habits directly over 4–6 months in a semiquantitative way (Nardoto et al., 2011, 2020). More details about the advantages of this interdisciplinary method can be seen in Jesus Silva et al. (2019).

2.3 Isotopic composition of food patterns

The analysis of the isotopic composition of food patterns followed the same methodology as Nardoto et al. (2020), differing only by the smaller number of samples to match the $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ fingernail values with the questionnaire data. Thus, each interview respondent donated a tiny piece of fingernail, with 736 sample units collected. The fingernail samples were cleaned with distilled water in a chloroform/methanol solution (2:1) and cut into 1–4 sections depending on the nail size. Then, they were weighed in small capsules (1–2 mg) before being subjected to isotopic analyses for carbon and nitrogen at the Isotopic Ecology Laboratory, CENA—USP.

The isotopic composition ratios ($^{13}\text{C}/^{12}\text{C}$ and $^{15}\text{N}/^{14}\text{N}$) from all sampling communities were determined using a Delta Plus mass spectrometer (Finnigan MAT) coupled with an elemental analyzer (Carla Erba model 1110). The isotopic results were presented as a deviation (δ) multiplied by 1000 (‰) according to the following equation:

$$\delta = (R_{\text{sample}}/R_{\text{standard}} - 1) \times 1000 \quad (1)$$

where R_{sample} is the ratio between the rare and most abundant isotopes (i.e., $^{13}\text{C}/^{12}\text{C}$ and $^{15}\text{N}/^{14}\text{N}$, respectively) of the fingernail samples and R_{standard} is the international standard used. The isotope ratios are reported in per mil (‰), where $\delta^{13}\text{C}$ is reported relative to the Vienna Pee Dee Belemnite (VPDB; $^{13}\text{C}/^{12}\text{C}$ ratio = 0.01118) standard and $\delta^{15}\text{N}$ is reported relative to atmospheric air (AIR; $^{15}\text{N}/^{14}\text{N}$ ratio = 0.0036765). Internal standards (tropical soil and sugarcane leaves) were routinely interspersed with target samples to correct for mass effects and instrumental drift during and between runs. The long-term analytical error for the internal standards was 0.2‰ for both $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$.

2.4 Statistical and spatial analysis

The suppositions of normality and homoscedasticity were tested through a residual analysis, Shapiro–Wilk, and Bartlett’s test of the residues, respectively. A Kruskal–Wallis nonparametric test for several independent samples was then carried out to verify the possible differences in $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values among treatments. A post hoc nonparametric *Dunn test* for multiple comparisons was applied after this to confirm significant differences between the groups.

First, we implemented these statistical routines to test for differences between the Brazilian states (i.e., AM, GO [Goiás], PA, and RN) and then among the types of rural communities (i.e., city, town, village, coast, and island). Finally, the same procedure was performed in a nested way to assess differences among the types of sites by each Brazilian state (Table 2). We then applied a generalized linear model (GLM) to verify the relation effect between theta’s values from the Bayesian groups (for both livelihood and agro-food dataset clusters) and isotopic ratios ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$) because of the non-normal data used.

Table 2 Mean ($\pm$ standard deviation; %) isotopic $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ of residents’ fingernails among the Brazilian states (AM Amazonas, GO Goiás, PA Pará, and RN Rio Grande do Norte), sites, or communities’ types (City, Town, Village, Coast, and Island), and between sites within each state. *N* number of samples

Treatment	$\delta^{13}\text{C}$	$\delta^{15}\text{N}$	<i>N</i>
States			
AM	$-20.14 \pm 1.31\text{a}$	$10.31 \pm 0.56\text{a}$	175
GO	$-18.15 \pm 1.34\text{b}$	$9.46 \pm 0.64\text{b}$	121
PA	$-18.70 \pm 2.39\text{b}$	$12.55 \pm 1.28\text{c}$	68
RN	$-16.87 \pm 0.63\text{c}$	$10.36 \pm 0.64\text{a}$	372
Sites			
City	$-17.60 \pm 1.49\text{a}$	$10.34 \pm 0.64\text{a}$	256
Coast	$-16.69 \pm 0.61\text{b}$	$10.61 \pm 0.76\text{a}$	36
Island	$-16.89 \pm 0.85\text{b}$	$13.49 \pm 0.77\text{b}$	39
Town	$-18.23 \pm 1.83\text{c}$	$10.05 \pm 0.72\text{a}$	339
Village	$-20.01 \pm 1.66\text{d}$	$10.55 \pm 0.86\text{a}$	66
Nested by state			
AM			
City	$-19.96 \pm 1.17\text{a}$	$10.41 \pm 0.56\text{a}$	54
Town	$-20.22 \pm 1.36\text{a}$	$10.27 \pm 0.55\text{a}$	121
GO			
City	$-17.07 \pm 1.04\text{a}$	$9.29 \pm 0.41\text{a}$	24
Town	$-18.01 \pm 1.07\text{b}$	$9.21 \pm 0.55\text{a}$	60
Village	$-19.14 \pm 1.24\text{c}$	$9.97 \pm 0.61\text{b}$	37
PA			
Island	$-16.89 \pm 0.85\text{a}$	$13.49 \pm 0.77\text{a}$	39
Village	$-21.12 \pm 1.46\text{b}$	$11.29 \pm 0.48\text{b}$	29
RN			
City	$-16.95 \pm 0.69\text{a}$	$10.45 \pm 0.56\text{a}$	178
Coast	$-16.69 \pm 0.61\text{a}$	$10.61 \pm 0.76\text{a}$	36
Town	$-16.81 \pm 0.56\text{a}$	$10.21 \pm 0.67\text{a}$	158

* Different letters represent statistically significant differences at $p < 0.01$ using a Dunn test

The statistical analyses were performed using R version 2.9.2 at a significance level of $p \leq 0.01$. This low α is related to the use of continuous data (isotope values) in nonparametric analysis and jointly with categorical or semiquantitative data in the GLMs, which was performed through the outputs of Bayesian results. The purpose of increasing the strength of the statistical tests was to minimize the chance or bias of a false positive result (type II error). We used the packages “Dunn.test” for the nonparametric analyses, glm function from “stats” for the crossing of questionnaire outputs and isotopic results, and “geobr,” “ggplot2,” “sf,” “dplyr,” and “rio” for the spatial analysis.

2.5 Bayesian clustering models of the questionnaire data

First, we detached the semi-structured questionnaires into two databases: (1) livelihood socioeconomic information and (2) agro-food data of hunting and gathering, subsistence farming, fishing, and food consumption. These datasets were then categorized into binary and integer values according to the nature of the variables). Posteriorly, both data were analyzed using a Bayesian mixture model to identify the main agro-food patterns and sort them according to different regions’ livelihood conditions.

We implemented a model in which individuals were clustered according to their socioeconomic characteristics and food consumption. This model is similar to a standard mixture model except that a parameter vector characterizes each location, and the number of groups is automatically determined through the use of a stick-breaking prior.

Features from each individual (e.g., socioeconomic variables or food consumption) were assumed to be discrete and arising from categorical distributions. For variable j associated with individual i at location l , we assumed that:

$$x_{ilj} | z_{il} = k \sim \text{Cat}(\psi_{jk})$$

where z_{il} is the latent cluster membership of individual i in location l . Notice that ψ_{jk} is a vector of probabilities that characterizes variable j for cluster k . We assumed that this latent variable z_{il} came from a categorical distribution:

$$z_{il} \sim \text{Cat}(\theta_l)$$

where θ_l describes the proportion of individuals in location l that come from each cluster, where the sum of probabilities of all groups for each location is equal to one. Then, we adopted stick-breaking priors with α and $\gamma=0.1$ to determine the correct number of groups and assumed that:

$$\psi_{jk} \sim \text{Dirichlet}(\alpha).$$

Finally, to automatically determine the optimal number of groups, we assumed that:

$$\theta_l \sim \text{TSB}(\gamma).$$

This implies that:

$$\theta_{lk} = V_{lk} \prod_{c=1}^{k-1} (1 - V_{lc})$$

$$V_{lk} \sim \text{Beta}(1, \gamma).$$

The log-likelihood for this model is given by:

$$\begin{aligned} &= \prod_l \prod_i \sum_k \left[\prod_j p(x_{ij} | z_{il} = k) \right] p(z_{il} = k) \\ &= \prod_l \prod_i \sum_k \left[\prod_j \psi_{jk}(x_{ij}) \right] \theta_{lk}. \end{aligned}$$

In general, this model is different from that in the EcoCluster package (see Valle, 2020) because of the parameters θ_l and the combination of the Bernoulli and multinomial random variables used here. Additionally, the low values set to the priors (α and γ) helped to prevent label change, a common problem in mixed-membership and mixture models, among other things related to the optimal number of groups formed and the proportion of parameters θ_{lk} (Valle, 2018).

This model was fitted using Gibbs samplers with 1,000 interactions, and the convergence was evaluated through a trace plot of the log-likelihood (Albuquerque et al., 2019). Therefore, the model fit assessment relied on the log-likelihood to verify if the Gibbs sampling has converged through the occurrence of an asymptotic pattern in the trace plot. Then, we tested the reliability of the Bayesian questionnaire results according to the stick-breaking low priors (α and γ) that prioritize a smaller number of groups. The maximum number of groups was set to 15 for both the socioeconomic and agro-food data analyses to determine the optimal number of clusters, which are not superfluous or very uncommon through all locations (Valle et al., 2018). Since the sum of θ_l for each location is equal to 1, it was possible to check the fraction between the sum of θ_l 's estimated values of optimal groups selected and the number of all regions l . Consequently, this afforded a representativeness index of the optimal clusters settled by the model that could be interpreted similarly to the cophenetic coefficient correlation of traditional clustering analysis. The package “MCMCpack” was used in R.

3 Results

3.1 Socioeconomic conditions

There was a significant difference between the sexes for all treatments, and overall, women comprised 70% of the interviewees. Regarding house conditions, in Apeú Salvador Island (Viseu county), all dwellings were stilt houses made from wood, whereas in the “coast” community in the Rio Grande do Norte State, all residences were masonry houses. The states with fewer masonry dwellings were PA and AM, with 1.5% and 39.5, respectively.

Considering general government assistance (GGA), 55% of all locations received some public aid such as *Bolsa Família* (family allowance), *Seguro-Defeso* (fishing spawning support), and Retirement, among others. While 63% of interviewees received GGA in the State of GO, this was 70% in AM, 39% in RN, and 82% in PA. Comparing among types of sites, except for the Island (which had 90% GGA), all other types of communities (city, town, coast, and village) had approximately 50% on average, with actual values slightly higher or lower than this.

Regarding schooling, incomplete elementary school was the most common educational attainment reported (Fig. 1). Despite the reports provided during interviews, we were able to identify a significant illiteracy level from the participant field observations. Through the ψ 's (ψ) estimated values (Fig. 1) of the socioeconomic data, it was possible to determine the optimal number of groups (four) according to the clustering of the livelihood variables.

The group with the best conditions was more representative of respondents with higher levels of access to electricity, masonry houses, high school graduation, self-employed, and female individuals, with fewer stilt or wood houses, retirees, and male interviewees (Fig. 1). In contrast, the worst-condition group was more representative of male respondents, Bolsa Família (family aid) beneficiaries, retirement allowance receivers, wood house dwellers, and higher illiteracy rate, with fewer masonry houses, private sector employees, and lower rates of high school graduates (Fig. 1). In brief, the dwelling conditions representativeness, house structure type, electricity access, education level, and gender were the main variables for clustering according to livelihood and socioeconomic conditions.

Regarding the θ 's (θ) estimated values of the socioeconomic data, it was possible to determine four optimal groups with their corresponding representativeness by location (Fig. 2). The index of representativeness of these four groups was 0.77 (i.e., 77% of accuracy), which demonstrates its suitability. By crossing these with ψ 's clustering results (Fig. 1), we could discriminate each group based on its socioeconomic condition. Thus, the communities of RN State and towns of the Alto Paraíso, GO (Fig. 2), had the best conditions. Conversely, the AM sites (overall) and the villages of Monte Alegre (GO) and Melgaço (PA) had the worst conditions (Fig. 2). Two of the most remote areas are located in these counties, the *Kalunga* slave remnant (GO) and Caxiuanã National Forest conservation unit (PA) (Fig. 2).

3.2 Agro-food patterns

Through the ψ 's (ψ) and θ 's (θ) estimated values of the agro-food dataset, it was possible to determine the optimal number of groups (three) and discriminate among them by location according to the proportion of the descriptive variables (Figs. 3 and 4). The index of representativeness of the agro-food model was 0.75 (i.e., 75% of accuracy), being just

Fig. 1 Bayesian clustering methodology by the ψ 's (ψ) estimated values (as % representativeness) to determine the optimal number of groups (four) according to the descriptive socioeconomic variables

Fig. 2 Bayesian clustering methodology by the theta's (Θ) estimated socioeconomic dataset values (as % representativeness) to determine the optimal number of groups (four) at each location. AM Amazonas; PA Pará; RN Rio Grande do Norte; GO Goiás

Fig. 3 Bayesian clustering methodology by the psi's (ψ) estimated values (as % representativeness) to determine the optimal number of groups (three) according to the descriptive agro-food variables. Highlighting that the difference here between poultry (free range) and chicken is regarding the farming system, raised outdoors or indoors in confined cages, respectively

as suitable as the previous one. The groups were sorted into “chicken and dairy” consumption, animal “creations and processed” foodstuffs, and “More Traditional” food items. Nevertheless, one or more variables may have had some representativeness in each specific group.

The chicken and dairy group showed the lowest indexes of manioc flour, poultry (free-range), cattle, and pigsties. Pork intake was also low in this group. In contrast, the creations and processed group had the highest pork consumption, although it was not very high (Fig. 3). This second group also had the highest beef, maize, wheat, sausages, poultry,

Fig. 4 Bayesian clustering methodology by the theta's (Θ) estimated values of the agro-food dataset (as % representativeness) to determine the optimal number of groups (three) at each location. AM Amazonas; PA Pará; RN Rio Grande do Norte; GO Goiás

cattle, and pigsties, while fish and game meat were the lowest. In contrast, these two items, plus fishing, vegetable gardens, coffee, and manioc flour, were the most representative in the more traditional group, while maize, wheat, beef, pork, sausages, chicken (factory farmed), eggs, vegetables, and fruits were the lowest (Fig. 3).

The crossing of the psi's (ψ) and theta's (Θ) estimated values enabled the determination of the agro-food standard noted above by each specific location (Fig. 4). The chicken and dairy curve had more representativeness in the Northeast's sites (RN) plus in the Center-West's communities of the Alto Paraíso county (GO). In contrast, this curve was less representative of the GO and PA states, more specifically in their villages and one island (Fig. 4).

The curve of creations and processed group was non-representative in almost all localities when compared to the curves of two other clusters; however, there were two representative peaks with 34% and 24% of town sites from Mossoró (RN) and Alto Paraíso (GO), respectively (Fig. 4). On the other hand, the more traditional curve was very representative in the most remote communities, specifically at the town and village sites of the *Kalunga* slave-remnant people from GO (Monte Alegre, Teresina, and Cavalcante counties) and the Caxiuanã riverine of PA (Melgaço county). Moreover, the Apeú Salvador Island from Viseu (PA) also had reasonable representativeness of more traditional food items (Fig. 4). On the other hand, all locations of AM, RN, as well as the area of Alto Paraíso (GO), had the lowest representativeness (%) of more traditional foods (Fig. 4).

By mapping the estimated theta's (Θ) values of respective groups, it was possible to see the same patterns but at a geographical scale, reinforcing where the best livelihood conditions are in Brazil's Northeast region (Fig. 5a). Similarly, this region also had more representativeness of chicken and dairy items plus animal creations and processed foodstuffs (Fig. 5b, c). Conversely, more traditional places were found in the Center-West and Eastern Amazon, with the riverine people of Caxiuanã (Melgaço, PA), and with the *Kalunga* slave-remnant groupings of Monte Alegre, Calvante, and Teresina counties, GO (Fig. 5c).

Fig. 5 Mapping of the estimated theta's (Θ) values of respective groups formed by the Bayesian clustering analysis. **a** Socioeconomic conditions. **b** Processed foods and animal raising. **c** Chicken and dairy consumption. **d** Traditional agro-food habits

Finally, crossing the Bayesian theta's values with the stable isotope ratios showed a significant difference only for the chicken and dairy groups regarding the $\delta^{13}\text{C}$ signal (Table 3), and there was a significant positive correlation between them. Moreover, only this first model with the three agro-food predictor groups was significant according to the predictive model probability of its dispersion parameter value (Table 3). Furthermore, no other model or specific predictor variable was statistically significant, except for “better conditions” in the crossing of the livelihood socioeconomic groups to the $\delta^{15}\text{N}$ values, if an α of 5% is considered (Table 3). Probably, this result comes from a bias due to the use of both categorical and continuous data. In this sense, the Better Condition group of Bayesian analysis could not influence the signal of $\delta^{15}\text{N}$ values, since the representativeness (%) of this cluster was very low in all localities (Fig. 2). This skewed result explains the option for an α of 1% (Table 3).

3.3 Isotopic composition of residents' fingernails

In general, there was a significant difference among the regions for $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values (Table 2). The state of AM in the western Amazon displayed the lowest mean $\delta^{13}\text{C}$ of fingernails ($-20.14 \pm 1.3\text{‰}$), which was significantly different from the other three states (GO, PA, and RN). The state of RN in the Northeast region had the highest average $\delta^{13}\text{C}$ ($-16.87 \pm 0.6\text{‰}$), while the states of GO (Center-West) and PA (Eastern Amazon) had intermediate values that did not significantly differ from each other (Table 2). However, these two states were also significantly distinct from the other two, with extreme $\delta^{13}\text{C}$

Table 3 General linear model association results for predictors of the stable isotope ratios of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values in residents' fingernails by all Bayesian groups (from agro-food and livelihood dataset clusters), with the dispersion parameter value (D) and predictive model probability (p)

Variables	β	S.E	t	p	D	p
$\delta^{13}\text{C}$					0.167*	< 0.01
<i>Intercept</i>	-21.22*	0.94	-22.53	< 0.01*		
Chicken and dairy	0.044*	0.012	3.53	< 0.01*		
Creations and processed	0.048	0.034	1.39	0.183		
More traditional	0.021	0.013	1.62	0.124		
$\delta^{15}\text{N}$					0.060	0.442
<i>Intercept</i>	11.24*	0.626	17.93	< 0.01*		
Chicken and dairy	-0.009	0.008	-1.13	0.273		
Creations and processed	-0.029	0.022	-1.29	0.215		
More traditional	-0.006	0.008	-0.76	0.458		
$\delta^{13}\text{C}$					0.241*	< 0.01
<i>Intercept</i>	-17.84*	1.41	-12.58	< 0.01*		
Best conditions	0.032	0.04	0.74	0.470		
Better conditions	0.048	0.06	-0.83	0.420		
Worse conditions	0.021	0.20	-0.24	0.808		
Worst conditions	0.005	0.21	0.02	0.981		
$\delta^{15}\text{N}$					0.333	0.031
<i>Intercept</i>	13.57*	0.752	18.03	< 0.01*		
Best conditions	-0.013	0.023	-0.56	0.579		
Better conditions	-0.080	0.035	-2.24	0.041		
Worse conditions	-0.156	0.106	-1.47	0.162		
Worst conditions	0.105	0.116	0.90	0.381		

* Statistically significant result

signals. The distribution of the $\delta^{13}\text{C}$ values was also different, mainly between the states of PA and RN (Fig. 6a). The carbon range was lowest in the Northeast region with a very homogeneous distribution (Fig. 6a), which was also expressed through its low variability (Table 2).

The $\delta^{13}\text{C}$ fingernail values also differed among sites and community types, mainly between villages and coasts. While villages had the lowest mean carbon signal, the coast and island were both the highest with a significantly less negative value of $\delta^{13}\text{C}$ than the other three categories of rural settlements (Table 2). Thus, all types of sites differed significantly from each other, except for the coast and island, which were similar (Table 2). The range of $\delta^{13}\text{C}$ values from these two locations was also the narrowest, denoting their relative data dispersion homogeneity with less variability than the other groups (Fig. 6b). The city and town sites were the most heterogeneous in the dispersion of $\delta^{13}\text{C}$ values (Fig. 6b).

The $\delta^{15}\text{N}$ fingernail values were also different among the state regions, being more pronounced between PA and GO, which were significantly different from each other (Table 2). Since the $\delta^{15}\text{N}$ mean was higher in PA and minor in GO, the states of AM and RN were similar (Table 2). On the other hand, the average nitrogen signals among the sites did not differ significantly, except for Apeú Salvador, which were considerably

Fig. 6 Box plots of average carbon ($\delta^{13}\text{C}$) and nitrogen ($\delta^{15}\text{N}$) isotopic values of the resident's fingernails by **a** state and **b** types of Brazilian rural communities. AM Amazonas; PA Pará; RN Rio Grande do Norte; GO Goiás. Different colors between boxes represent statistically significant differences

higher than the others (Table 2). Regarding data variability, the state of PA again had a greater range of $\delta^{15}\text{N}$ values (Fig. 6a), while the dispersion among sites was insignificant (Fig. 6b).

In addition to differences among the states and sites, dissimilarities between communities in each specific region, nested by state, were observed for GO and PA in the Center-West and Eastern Amazon regions (Table 2). There was a significant difference in GO communities, with villages having the smallest mean $\delta^{13}\text{C}$ value and the highest $\delta^{15}\text{N}$. Despite the significant difference among villages, towns, and cities for the average carbon value, the same was not observed for average $\delta^{15}\text{N}$, which was only statistically different for villages (Table 2). Cities and towns from GO were similar to their mean $\delta^{15}\text{N}$ (Fig. 7b).

The cities from GO had the highest average $\delta^{13}\text{C}$ values compared to towns and villages. The range of both $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values was smaller in cities, denoting a more homogenous pattern in GO (Fig. 7b). The range was higher for $\delta^{15}\text{N}$ signals at towns, even compared with villages (Fig. 7b). Concerning PA, its island had significantly higher average $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values than the village of Caxiuanã in Melgaço County. The range of $\delta^{15}\text{N}$ was also higher on the island, showing more variability than the Caxiuanã village (Fig. 7b). Although there was a lack of statistically significant differences between the sites in RN and AM, the RN locations had some of the highest mean $\delta^{13}\text{C}$ in cities, while towns in AM had the smallest (Table 2). Furthermore, the isotopic ranges of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ were very homogenous for both regions (Fig. 7a, d).

Additionally, the average carbon ($\delta^{13}\text{C}$) isotopic values of residents' fingernails decreased toward the western Amazon region—AM (Fig. 8). Conversely, the mean $\delta^{13}\text{C}$ value increased toward the Northeast and Alto Paraíso (GO), Center-West. The high mean carbon in the eastern Amazon (Apeú Salvador Island, Melgaço—PA) is a particular case that deserves more attention (Table 2 and Fig. 8). The mean $\delta^{15}\text{N}$ value displayed an increasing pattern toward the eastern Amazon (PA), being mostly intermediate in other regions (Fig. 8).

Fig. 7 Box-plot of average carbon ($\delta^{13}\text{C}$) and nitrogen ($\delta^{15}\text{N}$) isotopic values of the resident's fingernails by the regions of **a** Amazonas (AM), **b** Goiás (GO), **c** Pará (PA), and **d** Rio Grande do Norte (RN), according to the types of communities sampled (City, Town, Village, Coast, and Island). Different colors between boxes represent statistically significant differences

4 Discussion

The isotopic analysis and questionnaire results confirmed the agro-food change pattern toward urban areas, mainly because of the increasing trend of $\delta^{13}\text{C}$ from the most remote villages to more accessible cities and lower representativeness of the more traditional group in cities and towns. Although there were fewer significant differences in $\delta^{15}\text{N}$ among the sites, the carbon results indicate that remote villages still had more traditional food habits and livelihood activities (e.g., bushmeat, fishing, and cassava flour, among others). Those places with easy access to the market economy had higher mean $\delta^{13}\text{C}$ values, indicating a diet based more on C_4 items such as sweets, sausages, chicken, and dairy.

These general findings correspond to those of previous studies that highlight an urban–rural food transition process, but now on a much larger geographical scale and with a slightly different methodological approach (Jardim, 2020; Jesus Silva et al., 2017; Jesus Silva et al., 2019; 2011; Reinaldo et al., 2015; Rodrigues, 2016; Schor & Azenha, 2017). In a participant observation with *Kalunga's* slave-remnant communities of African descent, Jesus Silva et al. (2019) demonstrated an analogous food change process through an isotopic analysis and interview survey. Studying African communities, Correia et al. (2019) also found a similar food change pattern between hunter–gatherer groups and agriculturalist–pastoralists more integrated into the market economy.

The lowest carbon ($\delta^{13}\text{C}$) variability in both coast and island communities, fishing communities from RN and PA states, indicates the relative homogeneity of their food habits. Although these locations expressed the highest C_4 food signal at all sites, there was

Fig. 8 Mapping of average carbon ($\delta^{13}\text{C}$) and nitrogen ($\delta^{15}\text{N}$) isotopic values of the residents' fingernails by the region (state) of Brazilian rural communities

a significant qualitative difference in the carbon source between them. The staple food of Apeú Salvador Island (PA) is mostly seafood/marine fish, with an isotopic signal derived mainly from phytoplankton in the food chain (Nardoto et al., 2020).

In a study on the stable isotope composition of food and beverages in Brazil, Martinelli (2020) found a significant $\delta^{13}\text{C}$ mean difference between marine fish and freshwater fish of -17.4‰ and -32.7‰ , respectively. They also verified the lowest $\delta^{15}\text{N}$ mean value of farmed fish compared with marine fish and freshwater fish, which were 4.8‰ , 12.0‰ , and 11.4‰ , respectively (Martinelli et al., 2020). Thus, although a similar mean $\delta^{13}\text{C}$ existed between coast and island sites, the significantly lower $\delta^{15}\text{N}$ value of the coast confirmed that their food base does not come from a diet rich in marine fish, as would be expected according to Martinelli et al. (2020).

In contrast, the carbon isotopic signal of PA's island reflects a higher seafood and marine fish C_3 -based intake than C_4 items such as beef, chicken, and dairy, among others (Figs. 3 and 4). The same was not observed for the RN's coast $\delta^{13}\text{C}$ signal, where the higher carbon values reflected the influence of a "supermarket diet." In this regard, the significantly higher $\delta^{15}\text{N}$ values of the PA island site than other sites reinforced the notion of a traditional way of life for the artisanal fisherman of Apeú Salvador, PA.

The Bayesian questionnaire results also supported the maintenance of their fish intake, as the other curves (chicken and dairy and creations and processed) were less represented on this island from Viseu, PA. Since top chain fish species usually have higher values of $\delta^{15}\text{N}$ due to the natural enrichment of N protein along the food chain (Hardt, 2013), the lower $\delta^{13}\text{C}$ of the RN coast indicated a shift in food habits in this Northeast region. The significant positive GLM correlation between the chicken and dairy group and the $\delta^{13}\text{C}$ fingernail ratios also reinforced this supposition, since the RN communities had the highest representativeness of this group. Besides reflecting a direct connection between the Bayesian and isotopic methods, these results reflected an increase in the consumption of C_4 food-stuffs, especially chicken and dairy, and less manioc flour.

Unlike Apeú Salvador Island (PA), one of our study's remotest sites, the fishing communities from RN were replacing their fish and seafood intake by processed foods as accessibility to the market economy increased. In addition to the isotopic results, the Bayesian findings also showed a high frequency of chicken and dairy consumption in the coast group of Macau, RN. These unexpected results contradict the historically prominent fish consumption in Brazil's coastal regions (Carneiro, 2003). Some authors argue that greater purchasing power due to fishing sales has influenced this food change, especially among young people (Hanazaki & Begossi, 2010; Nardoto et al., 2020; Silva, 2018).

This premise of greater purchasing power also corresponds with our findings, in which the coastal inhabitants from the county of Macau (RN) had one of the best livelihood conditions of all the study sites. The socioeconomic influence on agro-food arrangements can also explain the highest mean $\delta^{13}\text{C}$ from the RN groupings, considering that all the Northeast regions have shown the best livelihood conditions and the most changed food habits. The lower $\delta^{13}\text{C}$ values of fingernails in the remote villages revealed an evident influence of C_3 plants on their food habits, with more traditional items such as fish, manioc flour, bushmeat, and fishing activities represented in these groups. These staple foods are strategic for adjusting to the protein and energy ingestion demands of remote environments with their natural seasonality (Murrieta & Dufour, 2004).

The higher $\delta^{15}\text{N}$ values in these remote areas also indicated that game meat consumption, in addition to fish, was a part of their daily routine. In this regard, the most significant mean $\delta^{15}\text{N}$ difference was observed in the villages of GO, particularly in the *Kalunga* slave-remnant rural communities in Brazil's Center-West region. In conjunction with the

low report of bushmeat intake, these high nitrogen isotopic patterns reveal a possible fear of these people regarding the Brazilian environmental crimes law, which forbids hunting practices (Jesus Silva et al., 2019).

By mapping the $\delta^{13}\text{C}$ x $\delta^{15}\text{N}$ of fingernails and crossing these with the Bayesian questionnaire analyses, we could determine the breadth of the agro-food transition according to the local livelihood conditions. Thus, it was possible to infer that, overall, rural communities were undergoing an agro-food change toward urban settings with the significant presence of supermarket goods as accessibility rose in remote areas. This matter was very evident through the isotopic comparison among the Brazilian state regions, among sites, and then in a nested analysis of sites inside each state. However, we detected that the remotest sites were able to maintain or rearrange their local staple C_3 -like foods (based mainly on manioc flour, fish, game meat, rice, and beans), despite the growing influence of the urban lifestyle.

Some authors have approached this subject of livelihood change and food sovereignty through adaptative adjustments (Folke, 2010; Hanazaki et al., 2012; Nguyen et al. 2015; Tiftonell, 2014). Others have argued that increased consumption of processed items has not impaired or disconnected people from their local traditional food habits in all locations (Piperata et al., 2016; Lima et al., 2019).

Many studies differ from this complex perspective, claiming that extra income (e.g., received through public policies) is the factor most likely to cause the replacement of locally produced food (Piperata, 2007, 2016; Sharaunga & Wale, 2013). Additional factors influencing the food transition were explored previously through a multinomial logistic regression model applied on small scales in the Amazon and Cerrado regions (Jesus Silva et al., 2017, 2019). In this study, we aimed to determine the most representative factors associated with the agro-food transition process and sort them by each specific location through Bayesian analysis of questionnaires.

In addition to one particular factor, a set of features appeared to drive the transition process from local, staple C_3 -base foods to C_4 -like supermarket foodstuffs at the household level, such as interviewee gender, housing conditions, and educational attainment, among other socioeconomic variables. Although some remote rural settings were able to maintain their traditional habits, we verified a substantial replacement of traditional foods by purchased foods as the accessibility to urban areas increased.

Thus, the consciousness of causes impacting agro-food systems and livelihoods will require pragmatic decision-making from local decision-makers, public authorities, and all stakeholders through a more sustainable and slower integration of these communities into the market economy. This gradual and sustainable integration in the market economy could be achieved through strategic social, and government policy action (i.e., as has been done for Seguro Defeso in the Apeú Salvador Island) to allow adaptative adjustments or delay the consequences of sociocultural and agro-food changes. Another alternative may be to generate income through their indoor activities and traditional knowledge to preserve food customs and improve local socioeconomic conditions without biocultural disruptions. Regarding forest communities, Paudel (2018) provided substantial evidence that local environmental resource management can improve economic outcomes and relieve food insecurity in rural households under vulnerable conditions.

Finally, this is the first time an approach involving a Bayesian clustering model was applied to questionnaire data and used with stable isotopes to assess socioeconomic development impacts on agro-food systems and livelihood conditions in rural communities. Through this interdisciplinary method, it was possible to identify the optimal groups or socioeconomic factors influencing the food transition in rural communities. Since the

accessibility to market economies and supermarket diets is changing the livelihood conditions in rural communities, this study tried to subsidize stakeholders and public policies regarding the risk of the collapse of local customs due to the food transition process.

As part of our future research, we will develop an indicator of the livelihood functional diversity to evaluate the heterogeneity of socioeconomic and agro-food adjustments arising from these changes in Brazilian rural communities. Besides, other future proposals are to evaluate the consequences of recent effects of the COVID-19 pandemic in the livelihood of rural communities and possible disruptions on their agro-food systems. In this global pandemic scenario, should we continue dealing with food sovereignty, or is it now more a matter of food safety? Unfortunately, we suppose that the livelihood conditions in Brazilian rural localities have worsened to simply maintaining basic survival, thus becoming more a food safety problem than issued food sovereignty, possibly due to the lack of governmental commitment and public awareness. In this regard, studies are already being carried out in the Amazon county of Tomé-Açu—PA aiming to evaluate this supposition in agroforestry communities.

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Declarations

Conflict of interest The authors declare no conflict of interest.

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