Increased in carbon isotope ratios of Brazilian fingernails are correlated with increased in socioeconomic status

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High $\delta^{13}$C in human tissues in Brazil indicate high consumption of $C_4$-based sources due to the consumption of highly processed food and animal protein. The significant positive correlation between the human developed index (HDI) developed by the United Nations Development Program, and fingernail $\delta^{13}$C at the county level proved to be useful as a new proxy in tracking human nutrition. Regions with higher HDI are those with higher consumption of highly processed food.

INTRODUCTION

Several studies have used the multi-isotope approach to track the geographic origin of human remains as well as human movement in forensic anthropology, but only a few studies have used it in association with socioeconomic status and dietary behavior changes. These studies have demonstrated the progressive substitution of local food staples by industrialized processed foods in the developing regions of the world (the so-called nutrition transition process). In this context, we explored stable isotopic analysis as a new proxy for human nutrition status across Brazil under the worldwide “global supermarket” dietary trend. Brazil is a middle-income country with contrasting inequitable geographic regions in terms of socioeconomic development, health, and educational services. We compared the carbon isotopic ratio of fingernails from residents of more economic developed regions of the country, where high consumption of processed food prevails, with the less developed regions, where locally produced food predominates, particularly staples like rice, beans, and cassava.

While $C_3$ plants have $\delta^{13}$C varying approximately from $-34$ to $-24\%$, $C_4$ plants have $\delta^{13}$C that varies from $-14$ to $-10\%$, with no overlap between these plant types. Therefore, in recent decades, carbon isotopic composition became a useful tool to track $C_3$ and $C_4$ carbon in biological systems worldwide. Despite the fact that pineapple that is a CAM plant that could confound a nutritional analysis, these plant types have no overlap between these plant types. Therefore, in recent decades, carbon isotopic composition became a useful tool to track $C_3$ and $C_4$ carbon in biological systems worldwide. Despite the fact that pineapple that is a CAM plant that could confound a nutritional analysis, these plant types 5. Therefore, in recent decades, carbon isotopic composition became a useful tool to track $C_3$ and $C_4$ carbon in biological systems worldwide.

RESULTS AND DISCUSSION

We found a strong positive sigmoidal correlation (Fig. 1) between these two parameters according to the Boltzmann's equation ($R^2$ adj. = 0.72, Reduced $\chi^2 = 1.55$ by Levemberg–Marquardt algorithm):

$$\delta^{13}C = \frac{-22.75( \pm 0.53) + 16.68 \cdot HDI}{1 + e^{-16.68( \pm 0.10)}}$$

In this sense, Eq. (1) suggests higher consumption of processed food in areas with higher HDI, where market integration and purchasing power are higher than less developed areas of the country. This finding is in line with Vale et al., confirming our initial hypothesis.

Using the Eq. (1), the $[\delta^{13}C]_m$ was estimated for the 5507 Brazilian counties (see "Methods" for definition) among 37 counties distributed in different geographic regions of Brazil (Fig. S1—Supplementary material).
[δ13Cm] was generated in order to shed light on spatial trends for the country (Fig. 2). Although we found a robust correlation, future investigations on fingernails δ13C in municipalities with contrasting [HDI]m and in different regions of Brazil should be conducted to validate our model. We see a clear spatial polarization between north and south with lower [δ13Cm] values in the north than in the south, which means that in the north, C3-like foods predominate in the diet, resembling Brazilian staple foods, while in the south, C4-like foods predominate, which represents a higher market integration and consumption of processed food (Fig. 2).

Therefore, if we accept that [δ13Cm] is a proxy for higher consumption of processed food and adherence to the supermarket diet, it seems that in the southern region, the so-called nutrition transition has already been completed, whereas in the northern region this transition is still taking place (Fig. 2).

If the [HDI]m continues to grow, especially in counties of the northern states of the country, we will see an increase in [δ13Cm], indicating the late stage of the nutrition transition and a predominance of the supermarket diet with a high degree of market integration. Future trends of [δ13Cm] in the southern states of the country are more difficult to predict, if this part of the country adopts a plant-based diet that includes lower consumption of meats coupled with higher consumption of whole grain cereals, legumes, and fruits, we predict a decrease in the [δ13Cm] of this region in the future.

The discussion above acknowledges that our model has potentially a limited time span according to the progress of the socioeconomic conditions of the country as a whole and its different regions. Our model also has a geographic-limited scope being only potentially valid in those countries where there are inexpensive sources of C4 dietary carbon, which is the case in most northern-temperate countries.

However, we believe that in countries like Brazil, the [δ13Cm] could be another tool for detecting macro-scale trends in nutrition in time and space, since as emphasized by Walls et al., it is not easy to evaluate nutrition trends in low and medium-income countries, and the isotopic approach shown here could be also useful in linking social-economic dimensions to dietary trends. In addition, it provides new perspectives in human forensic anthropology as a powerful tool for tracking human movement in the contemporary world under the “supermarket diet” trend.

**METHODS**

The carbon isotope ratio ([13C:12C]) was determined in fingernails of residents of 37 Brazilian counties totaling almost 4500 samples (Supplementary Table 1; Supplementary Fig. 1). Briefly, fingernails were collected from donors using fingernail clippers. Samples were then cleaned with a solution of distilled water, methanol, and chloroform. For this survey, an authorization by the official Brazilian human ethical committee was previously submitted, approved, and received the registration number of COET 053, Piracicaba, São Paulo, Brazil.

The carbon isotopic ratio ([13C:12C]) in these samples was determined through a Delta Plus mass spectrometer for isotopic ratios (ThermoFisher Scientific), in the Laboratory of Isotope Ecology, CENA (University of São Paulo). Brazil. The results were reported as the deviation (δ) in parts per thousand (%) relative to standard international references; δX = (Rsample/ Rstd) - 1) × 1000; where, X is carbon, R is the heavy to light isotope ratio for carbon ([13C:12C]) of the sample (Rsample), and of the standard (Rstd). VPDB-Vienna Pee Dee Belemnite. BBOT (Fisons Instruments [C6H6N2O2S] and “grounded leaves of sugarcane” were used as internal standards to calibration during analysis runs. Every ten runs, both internal standards were used as target sample. Long-term standard deviations of internal standards used at the Ecology Isotope laboratory are of 0.2‰ for carbon.

The fingernail δ13C aggregated at the municipality level ([δ13Cm]) was obtained by averaging the δ13C of all donors from a municipality.

The counties included in this study represent 0.7% of the 5,507 Brazilian counties, and ~10% of Brazil’s population (Supplementary Table 1). These counties were chosen due to opportunities created by several scientific projects that resulted in a series of publications9,7. Details on sampling can be found in these publications. Not all samples were obtained in the same year, and this fact could be a limitation resulting in biased findings if temporal changes were large. However, most of the samples (almost 70%) were obtained from 2008 to 2015; 23% from 2002 to 2006; and 10% after 2015. Another important source of variability could be the fact that in some regions only urban centers were sampled, whereas in others, mainly in the Amazon region, small isolated villages were also included. This is important to mention because we have shown in other publications that urban centers are fully market integrated, and more isolated villages are not; these villages tend to have lower δ13C than urban centers in the same county9.

The HDI was created in 1990 by the United Nations as a response to persistent criticism throughout the 1980s that economic development alone could not capture human development (http://hdr.undp.org/en/content/human-development-index-hdi). Brazil was the first country to
launch HDI at the municipality level (HDI\textsubscript{m}) using basically the same parameters of the HDI developed by the United Nations. We obtained HDI at the municipality level (HDI\textsubscript{m}) for 2010, the last available year for Brazilian counties (http://www.atlasbrasil.org.br).

Optimal parameters of the Boltzmann’s sigmoidal model were obtained using a Levenberg–Marquadt algorithm of the Origin software (ver 8.6, Originlab). The Boltzmann sigmoidal equation used in the present work was:

\[ y(x) = \frac{A_1 - A_2}{1 + e^{x_0 - x}} + A_2, \]  

(2)

where \( A_1 \) and \( A_2 \) are the equilibrium values of the dependent variable before and after the transition, respectively; \( x_0 \) is the inflection point and \( \delta \) is the slope of the curve that describes the behavior of the process during the transition. The fingernail \( \delta^{13}\text{C} \) values of each Brazilian municipality was obtained based on predictions of \( \delta^{13}\text{C}_{\text{m}} \), from [HDI\textsubscript{m}] according to the above equation, using municipality centroid geographic coordinates.

High consumption of seafood, with \( \delta^{13}\text{C} \) values close to \( C_4 \) crops, could show a false positive correlation between \( \delta^{13}\text{C} \) of human tissues and consumption of meats and processed food. However, due to its high price, seafood consumption in Brazil is rather low, even in coastal cities as well as in marine fishing villages.\textsuperscript{14}

DATA AVAILABILITY

The data used in this article is in the Table 1 of the Supplementary material.

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AUTHOR CONTRIBUTIONS

L.A.M. and G.B.N. wrote the first paper, P.J.D.-N. and J.P.S.-S. performed all statistical and geo-spatial analysis, F.J.V.C., T.B.K., and J.E. contributed to the analysis and interpretation of the data, as well as in revising several versions of this paper.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

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