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Heterogeneous effects of market integration on sub-adult body size and nutritional status among the Shuar of Amazonian Ecuador

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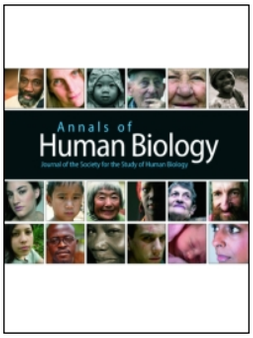
Abstract:

Market integration (MI)-increasing production for and consumption from a market-based economy-is drastically altering traditional ways of life and environmental conditions among indigenous Amazonian peoples. The effects of MI on the biology and health of Amazonian children and adolescents, however, remain unclear.This study examines the impact of MI on sub-adult body size and nutritional status at the population, regional and household levels among the Shuar of Amazonian Ecuador.Anthropometric data were collected between 2005-2014 from 2164 Shuar (aged 2-19 years) living in two geographic regions differing in general degree of MI. High-resolution household economic, lifestyle and dietary data were collected from a sub-sample of 631 participants. Analyses were performed to investigate relationships between body size and year of data collection, region and specific aspects of household MI.Results from temporal and regional analyses suggest that MI has a significant and overall positive impact on Shuar body size and nutritional status. However, household-level results exhibit nuanced and heterogeneous specific effects of MI underlying these overarching relationships.This study provides novel insight into the complex socio-ecological pathways linking MI, physical growth and health among the Shuar and other indigenous Amazonian populations.



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RESEARCH PAPER

Heterogeneous effects of market integration on sub-adult body size and nutritional status among the Shuar of Amazonian Ecuador

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ABSTRACT

Background: Market integration (MI)—increasing production for and consumption from a market-based economy—is drastically altering traditional ways of life and environmental conditions among indigenous Amazonian peoples. The effects of MI on the biology and health of Amazonian children and adolescents, however, remain unclear.

Aim: This study examines the impact of MI on sub-adult body size and nutritional status at the population, regional and household levels among the Shuar of Amazonian Ecuador.

Subjects and methods: Anthropometric data were collected between 2005–2014 from 2164 Shuar (aged 2–19 years) living in two geographic regions differing in general degree of MI. High-resolution household economic, lifestyle and dietary data were collected from a sub-sample of 631 participants. Analyses were performed to investigate relationships between body size and year of data collection, region and specific aspects of household MI.

Results: Results from temporal and regional analyses suggest that MI has a significant and overall positive impact on Shuar body size and nutritional status. However, household-level results exhibit nuanced and heterogeneous specific effects of MI underlying these overarching relationships.

Conclusion: This study provides novel insight into the complex socio-ecological pathways linking MI, physical growth and health among the Shuar and other indigenous Amazonian populations.

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Introduction

The Amazon Basin is undergoing increasingly rapid economic and environmental change (Malhi et al., 2008; Rodrigues et al., 2009; San Sebastián & Karin Hurtig, 2004). For many of the ~2 million indigenous Amerindians living in the region (Kronik &Verner, 2010), this process is associated with drastic transformations to traditional forager–horticulturalist ways of life. A growing number of native Amazonians are accessing national infrastructure and services (e.g. roads, electricity, medical care and formal education), engaging regularly in commercial activity and relying heavily on market foods and Western manufactured goods in their everyday lives. Diverse in nature and degree, this collective phenomenon of market integration (MI)—increasing production for and consumption from a market-based economy—has become a primary focus of Amazonian anthropological and human ecological research (Godoy et al., 2005; Hern, 1991; Lu, 2007; Santos et al., 1998; Valdivia, 2005). At the centre of this body of work has been investigation of the impact of markets on the biology and health of indigenous peoples, with particular interest in understanding the nature of relationships between MI and patterns of increasing adult overweight/obesity and chronic disease (Benefice et al., 2007; Brabec et al., 2007; Byron, 2003; Dangour, 2003; Godoy et al., 2006b; Gugelmin & Santos, 2001; Gurven et al., 2013; Liebert et al., 2013; Lindgärde et al., 2004; Lourenço et al., 2014; Santos & Coimbra, 1996; Silva & Eckhardt, 1994; Tavares et al., 2003; Welch et al., 2009; Zeng et al., 2013).

Despite intensive research among Amazonian adults, few studies have investigated the effects of MI on the biology and health of indigenous Amazonian children and adolescents. To date, a small number of studies have examined the impact of MI on Amazonian sub-adult biology by comparing body size and nutritional status cross-culturally among populations experiencing qualitative differences in general degree of MI (Blackwell et al., 2009; Dangour, 2001; Hidalgo et al., 2014; Santos & Coimbra, 1991). A handful of others have focused on community-level measures of market access (e.g. distance to town, road connectivity) to similarly investigate relationships between MI and anthropometry (Foster et al., 2005;

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Godoy et al., 2010; Wilson et al., 2011). These broad research approaches have yielded mixed results, providing evidence for cases of both positive (Dangour, 2001; Foster et al., 2005; Hidalgo et al., 2014; Santos & Coimbra, 1991; Wilson et al., 2011) and negative (Blackwell et al., 2009; Godoy et al., 2010) overall effects of MI on growth, nutritional status and health.

Although productive, research exploring macro-level associations between MI and sub-adult body size in Amazonia has been restricted in its ability to describe what are likely complex relationships linking ongoing cultural, environmental and biological changes. Such research has been, for example, unable to examine potentially heterogeneous effects of specific aspects of MI (e.g. particular changes in lifestyle, economy, disease ecology and diet) on child and adolescent biology or, critically, to investigate existing variation in MI within local communities (Peralta & Kainer, 2008). To address these limitations, several recent studies have begun to incorporate detailed, household-level measures of MI into Amazonian research. These studies have, with few exceptions (e.g. Godoy et al., 2010), relied on small sample sizes and considered only single measures of MI—including household degree of participation in commerce (Benefice et al., 2006, 2007; Houck et al., 2013), monetary income or material wealth (Ferreira et al., 2012; Godoy et al., 2006a, 2010) and traditional ethnobotanical knowledge (McDade et al., 2007)—but have found preliminary evidence for diverse effects of MI on the body size and health of young indigenous Amazonians.

The present study builds upon this research by examining the impact of MI on child and adolescent body size and nutritional status among the Shuar, an Ecuadorian Amerindian population experiencing rapidly increasing (but widely varying) degrees of MI and acculturation. Previous cross-cultural research suggests that Shuar growth and health are negatively affected by ongoing transitions into markets (Blackwell et al., 2009; Houck et al., 2013). However, robust within-population analyses investigating multivariate relationships between household measures of MI and body size have never been performed. Using high-resolution anthropometric, economic, lifestyle and dietary data from a sample of 2164 Shuar (2.0–19.9 years old), this study has two primary objectives. First, to determine the *overall*, cumulative impact of MI on Shuar sub-adult body size and nutritional status by testing for secular changes in child and adolescent height, weight, body mass index (BMI), and skinfold thicknesses over time (i.e. between the years 2005–2014), as well as for differences in these same measures between geographic regions experiencing general differences in MI. Second, to explore the *specific* impacts of MI on Shuar sub-adult body size and nutritional status by examining relationships between height, weight, BMI, skinfolds and distinct measures of household MI (i.e. relating to unique aspects of household economy, lifestyle and diet). This approach simultaneously assesses relationships between MI and child and adolescent anthropometry at the population, regional and household levels. Detailed analyses of this nature can provide insight into the complex factors linking MI, human biology and health.

Methods

Study population

The Shuar are a Jivaroan-speaking Amerindian population of ~40 000–110 000 individuals living predominantly in the Amazonas region of southeastern Ecuador (CODENPE, 2012; Rubenstein, 2001). Like many indigenous Amazonian groups, they traditionally inhabited small households scattered throughout the area and practiced a semi-nomadic lifestyle with a mixed subsistence pattern of swidden horticulture, foraging, hunting and fishing (Harner, 1984; Karsten, 1935; Rubenstein, 2001). Although they briefly came into contact with Spanish colonisers in the 16th century (De Velasco, 1841), sustained interactions with non-indigenous outsiders did not occur until the establishment of a small trading network with nearby Ecuadorian settlers during the late 1800s (Harner, 1984). This event, in conjunction with natural resource exploration and intensified missionary activity in the area beginning in the 1940s, resulted in the widespread distribution of certain basic manufactured items (e.g. machetes, woven cloth) throughout Shuar territory by the middle of the 20th century (Harner, 1984; Rubenstein, 2001). Despite nearly universal access to such items at this time, a large portion of the population did not experience direct contact with colonising outsiders until several decades later.

Today, the large majority of Shuar reside in one of over 600 small rural communities dispersed over a total area of ~30 000 km^2 (CODENPE, 2012). Accelerated economic development over the past decade has resulted in generally increasing but highly uneven degrees of integration into local, regional and national markets (de Salvador Agra & Martínez Suárez, 2015; Liebert et al., 2013; Lu, 2007). Market integration has been most concentrated in the historically and geographically more accessible Upano Valley (UV) region of Shuar territory, an area bound by the Andean foothills to the west and the rugged Cutucú mountain range to the east. The UV possesses most of the roads (some of them recently paved) available to the Shuar, is the location of several large towns with stores and services, and is directly connected by bus to Quito and other important Ecuadorian commercial, cultural and political centres. Many Shuar living in rural areas of the UV now possess electricity and rudimentary piped water. An increasing number also have access to Western medical care and formal education and regularly travel to town to perform wage labour or sell items at market. Although horticulture remains nearly universal, traditional hunting and fishing are no longer widely practiced among many UV Shuar (Liebert et al., 2013). In comparison to the UV, the cross-Cutucú (CC) region of Shuar territory directly to the east of the Cutucú range remains more isolated and much less economically developed. The CC currently possesses a single road linking it to outside areas, minimal electricity and piped water and limited infrastructure supporting participation in formal medical care, education or commercial activity. Travel to UV market centres from CC communities currently involves a motor canoe trip ranging from ~1–16 hours (highly dependent upon water levels) followed by a 7-hour bus ride, with some communities located more than a 1-day walk from navigable

rivers. Owing to their general isolation, most CC Shuar continue to engage heavily in traditional subsistence practices and consume a diet based on garden foods (e.g. sweet manioc, plantains, bananas and sweet potato) supplemented by fish, small game and wild forest products (Liebert et al., 2013; Lu, 2007; Zapata-Ríos et al., 2009). It is important to note that, although general economic, lifestyle and dietary differences exist between Shuar living in the UV and CC, significant variation in MI remains within each of these regions, often at the household level (Liebert et al., 2013).

Data collection

Cross-sectional data from 2164 Shuar participants ($n = 1098$ females; age =2.0–19.9 years) living in rural communities throughout the UV and CC regions of Shuar territory were included in the present study. All data were collected in coordination with the ongoing Shuar Health and Life History Project (SHLHP; http://www.bonesandbehavior.org/shuar) between 2005–2014. Exact estimates of age were available for the majority of individuals from official school records and/or government-issued identification cards. When available, age was also estimated and cross-checked using overlapping genealogies constructed from information provided by parents, teachers and other community members. All participants provided informed consent/assent, with additional parental consent for children under the age of 15 years (the local age of consent). Study methods were approved by village leaders, the Federación Interprovincial de Centros Shuar (FICSH) and the institutional review boards of the University of Oregon and Harvard University.

Measures of body size and nutritional status—height, weight, BMI and skinfolds

Anthropometric measures of body size and nutritional status were obtained for all study participants from two previously described SHLHP sources (Blackwell et al., 2009; Urlacher et al., 2016). Data from 1196 participants ($n = 587$ females; age =2.5–16.5 years) were collected during a health diagnostic study conducted by FICSH and the hospital Pio XII in collaboration with the SHLHP between October 2005 and August 2006. This study involved visits by teams of local physicians and nurses to schools in 31 UV and two CC communities in the Morona Santiago province of Shuar territory. Height and weight were measured for nearly all students in attendance on days of visits using conventional equipment and methods (Blackwell et al. 2009). Although not directly involved in study data collection, SHLHP personnel were active in data entry and analysis for this project and present during data collection in a number of participating communities. Between October 2007 and August 2014, data from an additional 968 participants ($n = 511$ females; age =2.0–19.9 years) were collected as part of ongoing SHLHP survey research in 11 UV and 11 CC Shuar communities located in the provinces of Morona Santiago and Zamora Chinchipe. Height was measured to the nearest 1.0 mm using a portable stadiometer (Seca Corporation 214, Hanover, MD). Weight was measured to the nearest 0.1 kg using an electronic scale (Tanita Corporation BC-534/BF-689, Tokyo, Japan). For 804 participants ($n = 422$ females), triceps and subscapular skinfolds were also measured to the nearest 0.5 mm using Lange calipers (Beta Technology, Santa Cruz, CA). BMI (kg/m^2) was calculated for all study participants from height and weight data.

Measures of household market integration—income, lifestyle and diet

Household-level MI data were collected for a sub-set of 631 SHLHP survey research participants through structured interviews with heads-of-household from a total of 220 unique households. Household MI data were not collected from health diagnostic study participants. Interview data were often collected on the same day as participant anthropometric data ($n = 283$ participants) and always within a corresponding period of less than 2 years (average time between measures =0.15 years). Informants were typically the parents of participants, but were occasionally other family members, non-related individuals or older participants if identified as head-of-household. For operational purposes, households are defined as domestic groups sharing a cooking area (Welch et al., 2009), with household size (i.e. total number of residents) recorded in each case.

Household income (US dollars/month) was calculated as the total reported monthly cash earnings for all members of a household from any commercial activity (e.g. wage labour, animal and produce sales, timber sales). Income in some households was reported to vary slightly from month to month. In such cases, individuals were asked to report average monthly earnings for the previous year.

Lifestyle data were collected using the Material Style of Life (MSL) survey (Bindon et al., 1997) modified for use among the Shuar (Liebert et al., 2013). The MSL survey records the reported ownership of household items relating to Shuar traditional (*T-SOL*), market-integrated (*M-SOL*) and household (*H-SOL*) style of life. The list items included in each measure of SOL are provided in Table 1 and were chosen following extensive ethnographic fieldwork among the Shuar and additional pilot testing to ensure variation in ownership and diverse representation of investment in a given SOL (Liebert et al., 2013). Final SOL scores were calculated as the fraction of total list items owned by a household (i.e. for T-SOL and M-SOL) or as the sum of list items scored (i.e. for H-SOL). In general, T-SOL reflects degree of investment in a traditional foraging lifestyle, M-SOL degree of investment in a market lifestyle and H-SOL degree of household permanence and access to regional infrastructure.

Additional measures of household diet were collected using a 19-item food frequency questionnaire developed specifically for the Shuar (Liebert et al., 2013). Reported household frequency of consumption (items/week) of specific market foods was recorded and then summed to produce outcome variables based on macronutrient groups relating to frequency of consumption of *market fats/sugars* (i.e. soda, potato chips, butter, oil, cookies and sweets), *market proteins* (i.e. beef, pork and milk) and *market carbohydrates* (i.e. rice, pasta and bread). These basic macronutrient groupings have

Table 1. Household variables used in the calculation of Shuar style of life (SOL) measures.

Traditional-SOL ($n = 6$)	Market-SOL ($n = 12$)	Household-SOL ($n = 7$)
Fishing hook/line	Radio	Floors (0 = dirt; 1 = palmwood; 2 = milled lumber; 3 = concrete; 4 = tile)
Hunting dog	Propane stove	Walls (0 = palmwood; 1 = mixed; 2 = milled lumber; 3 = cinder block)
Blowgun	Mobile phone	Latrine (0 = none; 1 = pit; 2 = indoor toilet without water; 3 = outdoor toilet with water; 4 = indoor toilet with water)
Firearm	Television	
Fishing net	Chainsaw	Water Source (0 = river/stream; 1 = well/outdoor pipe; 2 = indoor pipe)
Canoe	Bicycle	Electricity (0 = none; 1 = lights only; 2 = outlets)
	Refrigerator	Rooms (total number)
	Computer	Houses (total number)
	Outboard motor	
	Motorcycle	
	Car	
	Truck	

Items included are based on the Shuar-specific lists from Liebert et al. (2013), with slight modification in accordance with recent lifestyle and economic changes. Final SOL values are calculated as the fraction of total list items owned (for Traditional-SOL and Market-SOL) or as the sum of list items scored (for Household-SOL).

been used previously in Amazonian dietary research (Ivanova, 2010).

Data analysis

All anthropometric data were converted to age- and sex-specific *z*-scores prior to analysis. *Z*-scores for height-for-age (HAZ), weight-for-age (WAZ), BMI-for-age (BAZ), triceps skinfolds-for-age (TSZ) and subscapular skinfolds-for-age (SSZ) were calculated using US National Health and Nutrition Examination Surveys (NHANES III) references (Frisancho, 2008). Initial evaluation of NHANES III measures of HAZ, WAZ and BAZ revealed substantial non-linear variation by age in the sample, making interpretations about relative within-population differences difficult and requiring more complex statistical models. To address this issue, additional variables for HAZ, WAZ and BAZ were calculated using growth references created specifically for the Shuar from a large, mixed-longitudinal dataset that included the present sample (Urlacher et al., 2016). These Shuar-specific *z*-score measures were used in all statistical models.

Following *z*-score calculation, the accuracy and distributional normality of all data were assessed. No significant outliers were observed among any study variable. However, all seven measures of household MI (income, T-SOL, M-SOL, H-SOL, market fats/sugars, market proteins and market carbohydrates) were positively skewed and were, therefore, $\log_{10}$-transformed prior to modelling. Pearson bivariate correlation coefficients were calculated among these $\log_{10}$-transformed measures. Following the detection of modest correlations among several household MI variables, all independent predictors included in regression models were tested for multicollinearity using measures of tolerance and variance inflation factors. Results indicated acceptable levels of multicollinearity (i.e. all tolerances >0.3 and variance inflation factors <5.0). Model heteroscedasticity was assessed visually using residual plots and was found to be acceptable in all cases. Non-linear main effects of predictor variables were assessed (and dismissed) using quadratic fits in each model.

The study sample was stratified by sex and divided into two age groups—'children' (between the age of 2.0–9.9 years) and 'adolescents' (between the age of 10.0–19.9 years)—for all analyses. This was done *a priori*, recognising that sex and the initiation of puberty near the age of 10 years among the Shuar (Urlacher et al., 2016) possess numerous biological and social implications that are expected to affect relationships between MI, growth and nutritional status. Initial descriptive analyses were performed to characterise Shuar body size and nutritional status by age and sex, as well as to describe measures of household MI by geographic region (i.e. UV and CC). Two-tailed independent-samples *t*-tests were executed to evaluate the significance of regional differences in household measures of MI, providing an empirical test of the ethnographic observation that the UV is generally more market integrated than the CC.

To evaluate the cumulative, overall effects of MI on Shuar body size and nutritional status (Objective 1), analyses were performed to test for temporal trends in height, weight, BMI and skinfolds in the dataset as well as for regional differences in these measures. Multiple linear regression models were, thus, constructed (using data from both the health diagnostic and survey datasets) with anthropometric measures of interest as outcome variables, year of anthropometric data collection and region as predictor variables and age as an additional covariate. Year by region interaction terms were included in initial models to test for regional differences in temporal trends in nutritional status. However, these interaction terms did not approach significance in any analysis and were removed from all final models. A term reflecting season of data collection (i.e. rainy or dry) was also included in original models, but similarly did not approach significance in any analysis and was, therefore, removed. Age- and region-adjusted Spearman partial correlation coefficients (r) were calculated from all significant final models to describe the degree of association between year and anthropometric measures.

To investigate the specific effects of household-level measures of MI on Shuar body size and nutritional status (Objective 2), additional multiple linear regression models were constructed (using data from the survey dataset only) with anthropometric measures of interest as outcome variables, predictor variables (entered simultaneously) for all seven measures of MI and covariates for age, year of anthropometry data collection, region and household size (i.e. total number of residents). Household size was included in this analysis as it has previously been shown to influence Shuar childhood growth (Hagen et al., 2006). Season of data collection was included as an additional covariate in original models, but again did not approach significance in any analysis and was

removed for final modelling. Year by MI variable and region by MI variable interaction terms were also included in initial models to test for possible changes in relationships between specific aspects of MI and anthropometric measures over time or differences in these relationships between regions. However, these interaction terms did not approach significance in any analysis either and were, therefore, removed from final models. We acknowledge that this analysis does not explicitly account for possible covariance effects due to the occasional sampling of multiple individuals from the same households in the dataset. Mixed effects models including a random household term were initially created for this purpose. However, these analyses were restricted by generally insufficient numbers of repeats per household, and, as such, the decision was made to follow numerous other studies among Amazonians by using simpler multiple regression models for all final analyses (e.g. Benefice et al., 2007; Ferreira et al., 2012; Piperata et al., 2011; Stinson, 1996). Age-, year- and household size-adjusted Spearman partial correlation coefficients were calculated from all significant final models to ascertain the degree of association between MI variables and anthropometric measures.

All statistical analyses were performed using SPSS 22.0 (Chicago, IL) or R 3.0.3 (http://cran.us.r-project.org/), with results considered statistically significant at $p < 0.05$.

Results

Participant sample sizes and descriptive statistics for Shuar body size and nutritional status measures by age group and sex are presented in Table 2. Consistent with previous findings among the Shuar (Urlacher et al., 2016) and other indigenous Amazonians (Benefice et al., 2006; Foster et al., 2005; Orr et al., 2001), children and adolescents possessed low mean levels of HAZ and WAZ, but approximately normal levels of BAZ relative to US references. Measures of TSZ and SSZ were well below US median values among all age and sex groups.

Pearson bivariate correlation coefficients for household measures of MI are provided in Table 3. Household-level MI data for the entire sample and split by the UV and CC regions of Shuar territory are further summarised in Table 4. Results from independent samples *t*-tests demonstrated significant regional differences in all measures of MI, such that mean values for household income ($t = 3.91$, $p < 0.001$), M-SOL ($t = 5.05$, $p < 0.001$), H-SOL ($t = 7.31$, $p < 0.001$), market fats/sugars ($t = 9.56$, $p < 0.001$), market proteins ($t = 10.78$, $p < 0.001$) and market carbohydrates ($t = 10.74$, $p < 0.001$) were significantly greater in the UV than the CC. Conversely, mean T-SOL ($t = -5.19$, $p < 0.001$) was significantly greater in the CC than the UV. There was no significant difference between regions in mean household size ($t = 0.719$, $p = 0.473$).

Relationships between year of data collection, geographic region and anthropometry

Table 5 presents parameter estimates from multiple linear regression models investigating the effects of year of data collection and region on measures of Shuar body size and nutritional status. Year of data collection was significantly and positively related to anthropometric measures in the majority of evaluated models (Figures 1 and 2). Controlling for region, later year of data collection was associated with greater HAZ among male children ($p = 0.002$, partial $r^2 = 0.014$), female children ($p < 0.001$, partial $r^2 = 0.034$), male adolescents ($p = 0.041$, partial $r^2 = 0.012$) and female adolescents

Table 2. Sample sizes and descriptive statistics (mean, SD) for Shuar body size and nutritional status measures by age group and sex.

	Children (age 2.0–9.9 years)				Adolescents (age 10.0–19.9 years)			
	Females		Males		Females		Males	
	n	Mean (SD)	*n*	Mean (SD)	*n*	Mean (SD)	*n*	Mean (SD)
NHANES III *Z*-scores[a]								
HAZ	686	−1.66 (0.99)	691	−1.77 (1.06)	412	−2.04 (1.12)	375	−2.23 (1.02)
WAZ	686	−0.56 (0.73)	691	−0.88 (0.72)	412	−0.75 (0.73)	375	−1.14 (0.66)
BAZ	686	0.19 (0.69)	691	0.42 (0.74)	412	0.05 (0.62)	375	−0.10 (0.69)
TSZ	250	−0.66 (0.65)	231	−0.58 (0.75)	172	−0.83 (0.65)	151	−0.76 (0.55)
SSZ	250	−0.17 (0.62)	231	−0.18 (0.48)	172	−0.13 (0.61)	151	−0.19 (0.46)
Shuar-specific *Z*-scores[b]								
HAZ	686	−0.12 (1.02)	691	−0.01 (1.08)	412	0.03 (1.13)	375	0.03 (1.14)
WAZ	686	0.07 (1.08)	691	0.14 (1.07)	412	0.08 (1.10)	375	0.07 (1.15)
BAZ	686	0.15 (1.16)	691	0.09 (1.15)	412	0.00 (1.23)	375	0.23 (1.33)

HAZ: Height-for-age *z*-score; WAZ: weight-for-age *z*-score; BAZ: BMI-for-age *z*-score; TSZ: triceps skinfold *z*-score; SSZ: subscapular skinfold *z*-score.
[a]*Z*-score calculated using US NHANES III growth references (Frisancho, 2008).
[b]*Z*-score calculated using Shuar population-specific growth references (Urlacher et al., 2016).

Table 3. Pearson bivariate correlation matrix for $\log_{10}$-transformed measures of household market integration.

	Income	T-SOL	M-SOL	H-SOL	Market Fats/Sugars	Market Proteins	Market Carbs
Income	1	−0.116	0.418**	0.241**	0.288**	0.297**	0.428**
T-SOL		1	−0.029	−0.102	−0.179**	−0.227**	−0.200**
M-SOL			1	0.419**	0.417**	0.395**	0.428**
H-SOL				1	0.397**	0.407**	0.468**
Market Fats/Sugars					1	0.545**	0.656**
Market Proteins						1	0.679**
Market Carbs							1

($p < 0.001$, partial $r^2 = 0.065$). In similar fashion, year of data collection had a significant positive effect on WAZ among male ($p = 0.006$, partial $r^2 = 0.011$) and female children ($p < 0.001$, partial $r^2 = 0.022$), as well as male ($p = 0.003$, partial $r^2 = 0.023$) and female adolescents ($p < 0.001$, partial $r^2 = 0.078$). Relatively few significant relationships were observed between year of data collection and BAZ (female adolescents, $p < 0.001$, partial $r^2 = 0.030$), TSZ (female children, $p < 0.001$, partial $r^2 = 0.078$) and SSZ (no significant relationships). Results from the same regression analyses indicate that, independent of year of data collection, living in the UV (rather than the CC) was associated with significantly greater TSZ among male children ($p < 0.001$) and adolescents ($p = 0.020$), as well as significantly greater SSZ among female children ($p = 0.034$). No relationships reaching statistical significance were observed between region and HAZ, WAZ or BAZ in any model (all $p > 0.1$).

Relationships between household measures of market integration and anthropometry

Results from multiple linear regression models investigating relationships between household measures of MI and Shuar anthropometric measures are presented in Table 6. Numerous significant relationships were observed, with patterns varying greatly between measures and by age group and sex.

Table 4. Descriptive statistics (mean, SD) for Shuar household-level measures of market integration in the total sample and by geographical region.

	Total ($n = 220$)	Upano Valley ($n = 137$)	Cross-Cutucú ($n = 83$)
Household size (total # individuals)	6.95 (2.56)	6.85 (2.54)	7.11 (2.61)
Income ($/month)	145.28 (178.70)	153.81 (174.09)	128.10 (187.86)**
T-SOL	0.47 (0.45)	0.35 (0.37)	0.67 (0.50)**
M-SOL	0.23 (0.20)	0.27 (0.16)	0.16 (0.23)**
H-SOL	9.54 (3.99)	10.84 (3.32)	7.39 (4.08)**
Market Fats/Sugars (items/week)	5.17 (4.62)	6.84 (4.40)	2.21 (3.35)**
Market Proteins (items/week)	2.22 (2.75)	3.15 (2.90)	0.57 (1.35)**
Market Carbs (items/week)	5.01 (5.07)	6.98 (5.22)	1.54 (2.08)**

Non-transformed values are given. Log_{10}-transformed values were used to test for regional differences in mean values.
**Significant between-region mean difference at $p < 0.001$.

Diverse results were observed across models for household income, such that income was negatively related to HAZ ($p = 0.048$, partial $r^2 = 0.027$) and WAZ ($p = 0.041$, partial $r^2 = 0.029$) among female children but, conversely, was positively related to WAZ ($p = 0.019$, partial $r^2 = 0.067$) and BAZ ($p = 0.004$, partial $r^2 = 0.101$) among adolescent males. Demonstrating more consistent effects, T-SOL was negatively and significantly related to male childhood HAZ ($p = 0.029$, partial $r^2 = 0.032$) as well as female childhood HAZ ($p = 0.025$, partial $r^2 = 0.035$), WAZ ($p = 0.044$, partial $r^2 = 0.028$) and TSZ ($p = 0.045$, partial $r^2 = 0.028$). Significant negative relationships with body size and nutritional status were again observed for M-SOL, such that greater M-SOL was associated with lower BAZ among male children ($p = 0.044$, partial $r^2 = 0.027$) and lower WAZ among male adolescents ($p = 0.049$, partial $r^2 = 0.047$). In contrast, highly mixed results were observed for H-SOL, with H-SOL exhibiting a positive relationship with WAZ ($p = 0.031$, partial $r^2 = 0.042$) and BAZ ($p = 0.023$, partial $r^2 = 0.046$) among female adolescents, but a negative relationship with HAZ ($p = 0.002$, partial $r^2 = 0.063$) and WAZ ($p = 0.004$, partial $r^2 = 0.058$) among female children and a similar negative effect on SSZ ($p = 0.029$, partial $r^2 = 0.068$) among male adolescents. Dietary variables reflecting the consumption of market fats/sugars and market proteins were not significantly associated with body size in any model (all $p > 0.05$). Frequency of consumption of market carbohydrates, however, was significantly and positively related to WAZ ($p = 0.047$, partial $r^2 = 0.048$) and BAZ ($p = 0.045$, partial $r^2 = 0.049$) among male adolescents and negatively related to TSZ among female children ($p = 0.032$, partial $r^2 = 0.037$).

Discussion

This study provides a rare investigation of the impact of MI on sub-adult biology among a rapidly transitioning indigenous Amazonian population. Using a large dataset facilitating population, regional and household-level analyses, we have examined both the overall and specific effects of MI on measures of Shuar child and adolescent body size and nutritional status. Results provide insight into the complex socio-ecological pathways linking MI, sub-adult growth and health in the Amazon.

Table 5. Parameter estimates (β, SE) from multiple linear regression models investigating the effects of year of data collection and geographical region on measures of Shuar body size and nutritional status.

		Children (age 2.0–9.9 years)		Adolescents (age 10.0–19.9 years)	
		Females ($n = 716$)	Males ($n = 751$)	Females ($n = 436$)	Males ($n = 406$)
HAZ[a]	Year	*0.07 (0.02)***	*0.05 (0.02)**	*0.11 (0.02)***	*0.05 (0.02)**
	Region (UV)	−0.02 (0.10)	0.10 (0.11)	0.00 (0.13)	0.02 (0.16)
WAZ[a]	Year	*0.06 (0.02)***	*0.04 (0.02)**	*0.12 (0.02)***	*0.07 (0.02)**
	Region (UV)	−0.03 (0.11)	0.07 (0.11)	0.05 (0.13)	0.05 (0.16)
BAZ[a]	Year	0.01 (0.02)	−0.00 (0.02)	*0.08 (0.02)***	0.05 (0.03)
	Region (UV)	−0.03 (0.12)	0.02 (0.12)	0.13 (0.15)	0.03 (0.18)
TSZ[b]	Year	*−0.06 (0.02)**	0.01 (0.03)	−0.03 (0.03)	−0.03 (0.03)
	Region (UV)	0.06 (0.09)	*0.41 (0.10)***	0.08 (0.11)	*0.22 (0.09)**
SSZ[b]	Year	−0.02 (0.02)	−0.02 (0.02)	−0.01 (0.03)	−0.04 (0.02)
	Region (UV)	*0.18 (0.09)**	0.08 (0.07)	−0.06 (0.11)	−0.00 (0.08)

Data were collected between 2005 and 2014. Age was included as a covariate in all models. Significant results are shown in italics.
[a]Z-score calculated using Shuar population-specific growth references (Urlacher et al., 2016).
[b]Z-score calculated using US NHANES III growth references (Frisancho, 2008).
*$p < 0.05$; **$p < 0.001$.

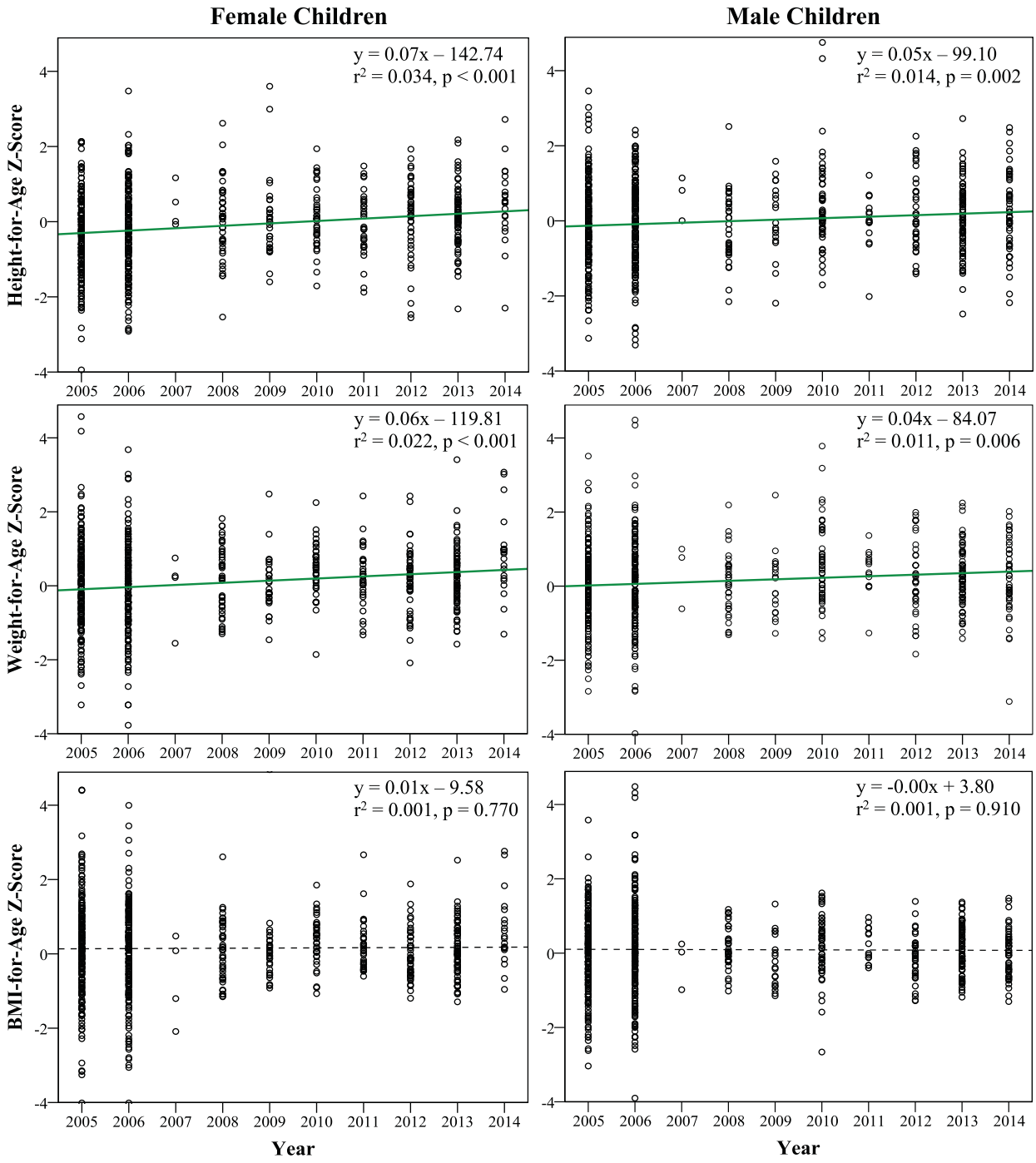

Figure 1. Shuar childhood (age 2.0–9.9 years) height-for-age, weight-for-age, and BMI-for-age z-scores by year of data collection. Females (left) and males (right). Solid green line = significant secular trend ($p < 0.05$). Dotted black line = non-significant secular trend. Z-scores were calculated using the Shuar-specific references of Urlacher et al. (2016).

Overall effects of market integration on Shuar body size and nutritional status

In contrast to previous research comparing the Shuar to other populations (Blackwell et al., 2009), the present study provides within-population evidence for overall positive effects of MI on Shuar sub-adult body size and nutritional status. Among children and adolescents of both sexes, year of data collection (i.e. a proxy for generally increasing levels of MI throughout Shuar territory) was positively related to HAZ and WAZ, such that individuals measured in any year between 2005–2014 were, on average, taller and heavier than their counterparts in previous years. A similar significant and positive secular trend was observed for adolescent female BAZ (but not BAZ among other individuals or skinfold thicknesses in any group). This evidence for general increases in Shuar growth and nutritional status accompanying advancing MI was corroborated by data demonstrating that living in the relatively more market-integrated UV, rather than the CC, was associated with significantly greater

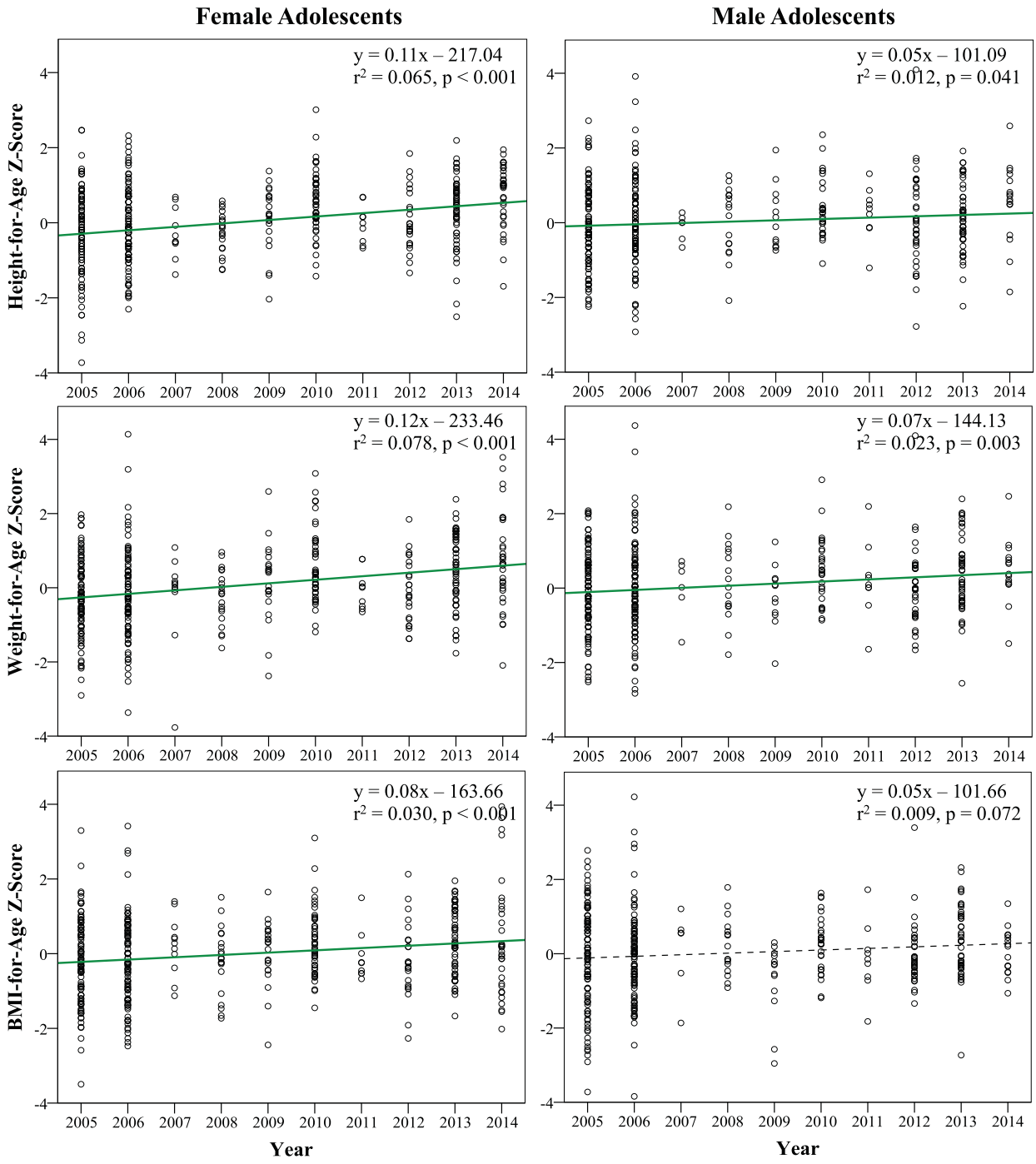

Figure 2. Shuar adolescent (age 10.0–19.9 years) height-for-age, weight-for-age, and BMI-for-age z-scores by year of data collection. Females (left) and males (right). Solid green line = significant secular trend ($p < 0.05$). Dotted black line = non-significant secular trend. Z-scores were calculated using the Shuar-specific references of Urlacher et al. (2016).

skinfold thicknesses in several models, regardless of year of data collection. Effect sizes for these relationships ranged from modest to large (0.04–0.12 *z*-score/year increases for secular trends and 0.18–0.41 *z*-score increases for UV residency) and explained ~1–8% of total observed variation in body size.

These findings for positive overall effects of MI on measures of Shuar body size and nutritional status are consistent with the majority of research exploring this topic elsewhere in Amazonia. Greater general levels of MI have, for example, been associated with greater child and adolescent HAZ among the Yanomamö and Guahibo of Venezuela (Hidalgo et al., 2014) and the Patamona and Wapishana of Guyana (Dangour, 2001), as well as greater child HAZ, WAZ and BAZ among the Tupí-Mondê of Brazil (Santos & Coimbra, 1991). Comparable studies evaluating secular trends in growth among Amazonian sub-adults remain limited, yet increases in Shuar body size between 2005 and 2014 again appear similar to those documented among the Matsigenka of Peru between 1977 and 1999 (Izquierdo, 2005) and mixed-ethnicity

Table 6. Parameter estimates (β, SE) from multiple linear regression models investigating the effects of household measures of market integration on Shuar body size and nutritional status.

		Children (age 2.0–9.9 years)		Adolescents (age 10.0–19.9 years)	
		Females ($n = 177$)	Males ($n = 201$)	Females ($n = 144$)	Males ($n = 109$)
HAZ[a]	Income	*−0.28 (0.14)**	−0.08 (0.16)	0.07 (0.14)	0.38 (0.32)
	T-SOL	*−1.46 (0.64)**	*−1.55 (0.71)**	−0.69 (0.59)	−0.03 (1.16)
	M-SOL	−0.21 (1.27)	0.63 (1.85)	−1.35 (1.37)	−3.15 (2.22)
	H-SOL	*−1.32 (0.43)**	−0.24 (0.53)	0.63 (0.52)	0.82 (0.81)
	Market Fats/Sugars	−0.17 (0.25)	−0.05 (0.29)	0.29 (0.30)	0.06 (0.55)
	Market Proteins	0.07 (0.32)	0.33 (0.41)	0.02 (0.37)	−0.51 (0.65)
	Market Carbs	0.29 (0.33)	0.17 (0.39)	0.14 (0.35)	1.12 (0.65)†
WAZ[a]	Income	*−0.31 (0.15)**	0.09 (0.16)	0.20 (0.17)	*0.64 (0.27)**
	T-SOL	*−1.41 (0.69)**	−1.33 (0.72)†	−0.53 (0.72)	−0.06 (0.97)
	M-SOL	0.60 (1.36)	−3.33 (1.89)†	−1.18 (1.68)	*−3.68 (1.85)**
	H-SOL	*−1.36 (0.46)**	−0.15 (0.54)	*1.38 (0.63)**	0.23 (0.68)
	Market Fats/Sugars	0.11 (0.27)	0.13 (0.30)	0.10 (0.37)	−0.57 (0.46)
	Market Proteins	0.11 (0.35)	0.60 (0.42)	0.15 (0.45)	−0.22 (0.54)
	Market Carbs	−0.01 (0.35)	0.06 (0.39)	−0.07 (0.43)	*1.07 (0.53)**
BAZ[a]	Income	−0.19 (0.13)	0.14 (0.18)	0.29 (0.17)†	*0.62 (0.21)**
	T-SOL	−0.47 (0.61)	−0.51 (0.80)	−0.05 (0.71)	0.80 (0.75)
	M-SOL	1.05 (1.19)	*−4.24 (2.03)**	−0.62 (1.65)	−1.88 (1.43)
	H-SOL	−0.63 (0.40)	0.15 (0.60)	*1.43 (0.62)**	−0.58 (0.53)
	Market Fats/Sugars	0.41 (0.24)†	0.33 (0.33)	−0.07 (0.36)	−0.66 (0.46)
	Market Proteins	−0.01 (0.30)	0.48 (0.46)	0.26 (0.44)	−0.17 (0.42)
	Market Carbs	−0.27 (0.31)	−0.18 (0.44)	−0.25 (0.42)	*0.85 (0.42)**
TSZ[b]	Income	0.15 (0.12)	−0.25 (0.14)†	0.14 (0.14)	0.06 (0.16)
	T-SOL	*−1.04 (0.52)**	−1.02 (0.60)†	0.24 (0.61)	−0.39 (0.58)
	M-SOL	−1.26 (1.04)	2.43 (1.51)	1.07 (1.16)	1.64 (1.05)
	H-SOL	0.15 (0.36)	−0.11 (0.46)	0.15 (0.48)	−0.12 (0.42)
	Market Fats/Sugars	0.34 (0.22)	−0.33 (0.25)	0.16 (0.28)	−0.05 (0.27)
	Market Proteins	−0.23 (0.28)	−0.37 (0.35)	−0.57 (0.32)†	0.54 (0.33)
	Market Carbs	*−0.59 (0.27)**	0.47 (0.32)	0.46 (0.32)	−0.21 (0.33)
SSZ[b]	Income	−0.02 (0.07)	0.06 (0.09)	0.08 (0.13)	0.09 (0.12)
	T-SOL	−0.36 (0.31)	−0.06 (0.39)	0.39 (0.55)	−0.52 (0.43)
	M-SOL	0.07 (0.60)	−0.50 (0.98)	1.18 (1.04)	−0.05 (0.78)
	H-SOL	−0.26 (0.21)	−0.18 (0.30)	0.15 (0.43)	*−0.70 (0.31)**
	Market Fats/Sugars	0.16 (0.13)	0.07 (0.17)	0.19 (0.25)	−0.01 (0.20)
	Market Proteins	−0.16 (0.16)	0.17 (0.24)	−0.23 (0.29)	−0.38 (0.25)
	Market Carbs	−0.06 (0.16)	−0.13 (0.21)	0.11 (0.29)	0.13 (0.24)

Measures of market integration ($\log_{10}$-transformed) were entered simultaneously in all models, with age, year of data collection, region and household size included as additional covariates. Significant results are shown in italics.
[a]*Z*-score calculated using Shuar population-specific growth references (Urlacher et al., 2016).
[b]*Z*-score calculated using US NHANES III growth references (Frisancho, 2008).
†$p < 0.1$; *$p < 0.05$.

Brazilian Ribeirinhos between 2002 and 2009 (Piperata et al., 2011). It is notable, however, that we have found much stronger evidence for positive secular trends across a range of anthropometric measures than these previous studies. This finding may be attributable to distinctive population-level relationships between MI and sub-adult biology or, alternatively, may reflect superior analytical power of the present study (i.e. owing to larger sample sizes and the use of population-specific anthropometric *z*-scores that better reflect meaningful within-population variation in body size). Among indigenous Amazonians, the nutritional transition (Popkin & Gordon-Larsen, 2004) and increased access to healthcare are typically invoked to explain positive relationships between general levels of MI and sub-adult body size (Dangour, 2001; Hidalgo et al., 2014; Santos & Coimbra, 1991).

Specific effects of market integration on Shuar body size and nutritional status

Although informative in many ways, regional and temporal analyses investigating the impact of MI on measures of body size do not permit identification of the specific aspects of MI driving observed biological changes. Nor can they account for existing variation in MI within geographic regions and communities that may obscure underlying relationships (Liebert et al., 2013; Peralta & Kainer, 2008). To directly address these issues, the present study is among the first in Amazonia to incorporate high-resolution, household-level measures of MI into multivariate analyses of sub-adult anthropometry (Godoy et al., 2010; Piperata et al., 2011). Results suggest heterogeneous effects of MI on Shuar child and adolescent growth and nutritional status. The biological significance of such effects appears to be in many cases quite large, with single household measures of MI accounting for as much as 10% of total observed variation in body size.

Income

Household income, a measure of MI relating to market production via labour and commerce, demonstrated varying effects on Shuar body size and nutritional status. Among female children, increased income was associated with lower HAZ and WAZ. However, an opposite positive relationship was observed between income and WAZ and BAZ among adolescent males.

To explain similar findings of a negative relationship between household income and child growth in height, Godoy

et al. (2010) have suggested that MI among the Bolivian Tsimane' is associated with changes in consumer decision-making that adversely affect diet. More specifically, they suggest that Tsimane' households with greater income are more likely to purchase highly visible luxury items (e.g. radios and televisions) and less likely to purchase market foods that are beneficial to child growth but of relatively low visibility and prestige (Godoy et al., 2010). A similar shift in resource allocation could explain the negative relationship between income and child body size observed among the Shuar. However, it cannot satisfactorily explain why female children are more strongly affected by income or why Shuar adolescent males demonstrate opposite, positive relationships between income and body size. Furthermore, our data suggest significant positive, rather than negative, correlations between income and household consumption of market foods, suggesting that Shuar households with greater income are indeed purchasing more dietary items.

Given the available information, a more robust socio-ecological explanation for observed effects of income on Shuar body size may relate to the relative ability of individuals of different ages and sexes living in the same households to access available market foods. Our ethnographic observations of Shuar social organisation and family dynamics suggest that older individuals, particularly males, are most likely to obtain valued market items entering households. As such, greater income may increase the availability of nutrient-dense market foods disproportionally for adolescent males (thereby supporting larger body size), while younger children, particularly females, may in fact experience little associated change in market food consumption and possibly even lower energy/nutrient intake due to simultaneous reductions in traditional food availability (thereby restricting growth and body fat deposition). Age- and sex-related differences in relationships between Shuar household dietary variables and nutritional status measures provide initial support for this hypothesis (see *Diet* discussion). Detailed behavioural and individual dietary consumption data are currently being collected for more complete testing.

Traditional style of life (T-SOL)

This is among the first research in Amazonia to evaluate the relationship between household ownership of traditional foraging items and sub-adult body size, providing insight into the link between investment in traditional foraging lifestyle and child and adolescent development in the context of rapid MI. Differing substantially from patterns observed for income, T-SOL exhibited consistent negative relationships with Shuar childhood, but not adolescent, anthropometric measures. These relationships were significant in both sexes, such that greater investment in traditional foraging lifestyle was associated with lower HAZ among male children and lower HAZ, WAZ and TSZ among female children, independent of other lifestyle, economic and dietary MI factors. Interestingly, T-SOL was not significantly correlated with M-SOL, H-SOL or income, suggesting that many Shuar households continue to invest in a traditional foraging lifestyle despite increases in several other aspects of MI.

We suggest two possible pathways linking greater Shuar T-SOL to lower measures of childhood body size. First, children living in households investing heavily in a traditional foraging lifestyle are expected to engage frequently in various foraging-specific and energetically costly behaviours (e.g. trekking, food processing), possibly increasing total physical activity energy expenditure and decreasing energy available for physical growth and body fat deposition. Second, greater investment in a foraging lifestyle may also be related to increased childhood pathogen exposure (i.e. resulting from increased contact with wild disease vectors), thereby elevating the activity of the immune system and similarly diverting energy away from physical growth. Such tradeoffs between growth and immune activity are expected to be most severe among young individuals whose immune systems are still developing (McDade, 2003), perhaps explaining why T-SOL is found to have a negative impact on a Shuar child but not adolescent body size. We note that greater T-SOL is indeed associated with increased odds of infection by soil-transmitted helminths among the Shuar (Cepon-Robins, 2015). The negative impact of helminth infection on childhood body size has, in turn, been demonstrated among several indigenous Amazonian populations (Berlin & Markell, 1977; Jardim-Botelho et al., 2008; Sackey et al., 2003) and is likely mediated through energetic pathways (Blackwell et al., 2010, 2011).

Market-integrated style of life (M-SOL)

In contrast to several other specific MI factors examined in this study, M-SOL, a measure of household market consumption relating to the ownership of durable manufactured goods, demonstrated few relationships with Shuar anthropometric measures. Increased M-SOL was associated with significantly lower BAZ among male children and lower WAZ among male adolescents, but was not significantly related to anthropometric measures in any other model. These results suggest that investment in a market-integrated material lifestyle has limited, although possibly slightly negative, effects on Shuar growth and nutritional status.

Lack of positive relationships between Shuar M-SOL and sub-adult body size is somewhat surprising, particularly given well-documented associations between the ownership of certain evaluated household items (e.g. televisions), low sub-adult physical activity and overweight/obesity in the developing world (Dollman, 2005; Lopes et al., 2014; Malina et al., 2008). It must be noted, however, that the Shuar evaluated in the present study are currently at a relatively early stage of MI and own few manufactured items. Relationships between Shuar M-SOL and body size may become evident in the future as levels of MI continue to increase.

Household style of life (H-SOL)

Shuar H-SOL—a measure of household physical permanence and access to modern infrastructure—exhibited multiple and mixed relationships with sub-adult body size. Greater H-SOL was associated with lower HAZ and WAZ among female children and lower SSZ among male adolescents but, in contrast, was associated with greater WAZ and BAZ among female adolescents.

We offer two socio-ecological hypotheses explaining these mixed relationships, both requiring additional data to be fully tested. First, the positive impact of H-SOL on adolescent female WAZ and BAZ may be explained by underlying reductions in physical activity accompanying improved household infrastructure. Access to piped water and electricity, for example, are expected to translate into reduced workloads for Shuar adolescent females who are typically responsible for the intensive tasks of fetching water and collecting firewood (Harner, 1984). Energy savings resulting from such behavioural shifts—estimated to be substantial elsewhere in Latin America (Kramer & McMillan, 1998)—could be re-allocated toward reproductively-important weight gain among adolescent females, ultimately leading to observed relationships between H-SOL and body size. Second, inverse relationships between H-SOL and HAZ and WAZ among Shuar female children may be explained by greater pathogen exposure accompanying a higher degree of household permanence, increasing immune activity and reducing energy available for growth as previously described (see *T-SOL* discussion). This hypothesis is supported by research among several indigenous Amazonian populations, demonstrating close associations between greater household permanence/MI and increased rates of infection by helminths and other common parasites (Eisenberg et al., 2006; Fitton, 2000; Hames & Kuzara, 2003; Santos et al., 1998; Tanner, 2014).

Diet—market fats/sugars, market proteins and market carbohydrates

Diet has long been a primary topic of research among indigenous Amazonians (Dufour, 1991, 1992; Milton et al., 1991), yet little is known about the effect of MI on local dietary patterns or the impact of such changes on sub-adult growth and nutritional status. Data that do exist suggest that, similar to elsewhere in the developing world (Popkin & Gordon-Larsen, 2004), MI in Amazonia is associated with the gradual replacement of traditional diets by calorically-dense market foods high in saturated fats and sugars (Da Silva & Begossi, 2009; Ivanova, 2010; Murrieta & Dufour, 2004; Murrieta et al., 1999; Piperata, 2007). We have provided preliminary evidence for such transitions among the Shuar, finding that household consumption of market fats/sugars, market proteins, and market carbohydrates is significantly greater in the relatively more market-integrated UV region of Shuar territory than in the CC. However, our results provide only minimal evidence supporting an impact of such changes on Shuar sub-adult anthropometry. No significant associations were observed between the reported frequencies of consumption of market fats/sugar or market proteins and body size in any evaluated model. A small number of significant relationships were observed between market carbohydrates and measures of body size, such that increased consumption of market carbohydrates was related to greater WAZ and BAZ among male adolescents, but lower TSZ among female children.

The present study lacks the detailed food quantity and composition data necessary to fully examine the impact of MI on Shuar diet or interpret observed relationships between dietary variables and anthropometric measures. However, we note that MI among other indigenous Amazonian populations has been shown to have a generally negative impact on overall dietary quality, diversity and food security (Godoy et al., 2005; Roche et al., 2008; Zorini & Lombardi, 2002). These factors, in turn, appear to negatively impact physical growth and nutritional status among Amazonian children (Benefice et al., 2006), but not adults (Zeng et al., 2013). As described above (see *Income* discussion), the non-uniform distribution of market foods among individuals of different ages and sexes living in the same household may help explain these contrasting patterns.

Implications for Shuar child and adolescent health

The Shuar and other indigenous Amazonian populations experience large disparities in health relative to their non-indigenous counterparts in the region, incurring higher rates of all-cause morbidity and mortality (Coimbra Jr et al., 2004; Hurtado et al., 2005; Kuang-Yao Pan et al., 2010; Larrea & Kawachi, 2005; Valeggia & Snodgrass, 2015). The role of MI in mediating these differences represents an important topic of research for human biologists. Among the Shuar (Liebert et al., 2013; Lindgärde et al., 2004) and other Amazonian groups (Benefice et al., 2007; Gugelmin & Santos, 2001; Port Lourenço et al., 2008; Welch et al., 2009), greater levels of MI have been linked to increased rates of adult overweight/obesity and risk of chronic disease (e.g. heart disease, type II diabetes), suggesting that recent MI has largely deleterious effects on adult health. The findings of the present study provide insight into the relatively unknown impact of MI on the nutritional status and health of indigenous Amazonian children and adolescents.

The positive overall relationship between MI and body size documented in this study suggests a generally beneficial impact of recent MI on Shuar sub-adult health. Indeed, levels of MI (evaluated broadly via temporal and region analyses) were associated with greater long-term (i.e. HAZ) and short-term (i.e. WAZ, BAZ, TSZ and SSZ) measures of child and adolescent nutritional status. Given that the Shuar are in general short and light relative to international references (Urlacher et al., 2016) and exhibit only very rare occurrence of clinically-defined overweight/obesity (0.7% $BAZ_{NHANES} \geq 2.0$; 0.1% $BAZ_{NHANES} \geq 3.0$), observed macro-level impacts of MI on anthropometry appear to promote improvements in modest population-level under-nutrition rather than deleterious increases in over-nutrition that could put individuals at risk for chronic disease and poor later life health (Dietz, 1998; Gluckman & Hanson, 2006). This interpretation is supported by findings among other indigenous and mixed-ethnicity Amazonian groups demonstrating no association between MI and rates of sub-adult overweight/obesity during similar stages of economic development (Benefice et al., 2007; Piperata et al., 2011). Critically, however, the impact of MI on Shuar nutritional status, if continuing unchanged, may soon result in increased incidence of overweight/obesity and negative impacts on health. Such deleterious effects may, in fact, already be apparent among Shuar children and adolescents living in urban areas characterised by high levels of MI not evaluated in this study. Our finding that Shuar adolescent females are experiencing particularly strong positive

secular trends in body size suggests that this group may be most at risk for future chronic disease and poor metabolic health. Greater understanding of possible differences in growth potential (Urlacher et al., 2016) and body proportions (Hruschka et al., 2015; Martorell, 2001; Post & Victora, 2001; Victora, 1992) between indigenous South Americans and US references is needed to better interpret the health implications of observed changes in Shuar body size.

The heterogeneous effects of specific aspects of household MI on Shuar child and adolescent body size demonstrate the complexity of relationships linking MI and health in this population. This is most clearly illustrated by certain cases in which the same measures of household MI (e.g. income, H-SOL) exhibit contrasting positive, negative and negligible impacts on body size among individuals of different ages and sexes. Future work will synthesise cultural, behavioural, biological and dietary data to test hypotheses aimed at understanding these relationships and determining the most effective targets for health promotion and intervention among the Shuar. Results suggest that studies investigating relationships between MI, immune activity and physical growth are particularly promising in this regard.

Study limitations

Two important limitations of this study must be considered. First, we have used cross-sectional data that restrict our ability to detect relationships between MI and Shuar individual-level physical growth over time. Future research in this population will address this issue by investigating longitudinal measures. Second, this study has focused exclusively on Shuar from rural communities, preventing reliable inference about relationships between MI and sub-adult anthropometry in urban areas experiencing greater degrees of MI.

Conclusions

This study has used population, regional and household-level analyses to provide rare insight into the relationships linking MI with sub-adult growth, nutritional status and health among an indigenous Amazonian population. Results suggest that increased MI among the Shuar is associated with positive overall effects on childhood and adolescent anthropometry. However, high-resolution analyses examining variation in specific aspects of household MI reveal substantially more complex and heterogeneous underlying relationships. These findings contribute to growing recognition of the multi-faceted impacts of MI on the biology and health of indigenous Amazonian peoples (Godoy et al., 2010; Liebert et al., 2013; Lu, 2007). Ongoing work among the Shuar will continue to explore the cultural, behavioural and environmental pathways through which MI imposes its biological effects, with a particular focus on identifying the factors most critical to health.

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