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RESEARCH PAPER

Birth seasons and heights among girls and boys below 12 years of age: lasting effects and catch-up growth among native Amazonians in Bolivia

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ABSTRACT

Background: Seasons affect many social, economic, and biological outcomes, particularly in low-resource settings, and some studies suggest that birth season affects child growth.

Aim: To study a predictor of stunting that has received limited attention: birth season.

Subjects and methods: This study uses cross-sectional data collected during 2008 in a low-resource society of horticulturists-foragers in the Bolivian Amazon, Tsimane'. It estimates the associations between birth months and height-for-age Z-scores (HAZ) for 562 girls and 546 boys separately, from birth until age 11 years or pre-puberty, which in this society occurs ~13–14 years.

Results: Children born during the rainy season (February–May) were shorter, while children born during the end of the dry season and the start of the rainy season (August–November) were taller, both compared with their age–sex peers born during the rest of the year. The correlations of birth season with HAZ were stronger for boys than for girls. Controlling for birth season, there is some evidence of eventual partial catch-up growth, with the HAZ of girls or boys worsening until ~ age 4–5 years, but improving thereafter. By age 6 years, many girls and boys had ceased to be stunted, irrespective of birth season.

Conclusion: The results suggest that redressing stunting will require attention to conditions *in utero*, infancy and late childhood.

Introduction

In 2014, stunting affected ~24% of children below 5 years of age globally (UN 2016), with most stunting found in low-resource settings (de Onis et al. 2013). Stunting is a public health concern because it correlates negatively with brain development and function, good health, energy, motor development, and exploratory behaviours, and, through some of these paths, covaries negatively with educational attainment, cognitive skills, wages, adult productivity, and birth weight of offspring (Berkman et al. 2002; Victora et al. 2008; Behrman et al. 2009; Hoddinott et al. 2013; Walker et al. 2015). Stunting is defined as being two standard deviations (SD) or more below the median height-for-age Z-score (HAZ) of a well-nourished international reference population (WHO 2006; de Onis et al. 2012; UNICEF, WHO, & WB 2012).

Stunting reflects chronic malnutrition (Shinsugi et al. 2015) and poor health (Guerrant et al. 2013; Bourke et al. 2016), which are associated with a host of predictors (Black

et al. 2017; Richter et al. 2017), such as low socio-economic status (SES) (Lee et al. 2010), membership in disadvantaged minorities (Reurings et al. 2013), armed conflict (AlDoori et al. 1994; Akresh et al. 2011), natural disasters (Dong et al. 2014), neglect (Loman et al. 2009; Hearst et al. 2014), inadequate parenting (Iwaniec 2004), and orphanhood (Finlay et al. 2016). These predictors increase children's risks of dying from infectious diseases (Prendergast and Humphrey 2014; Bourke et al. 2016) and of reduced children's neurological, cognitive, and motor development (Fernald and Grantham-McGregor 1998; Aburto et al. 2009; Marques et al. 2013) and reduced educational attainment and skills (Victora et al. 2008; Hoddinott et al. 2013), with consequences that persist into adulthood (Alderman et al. 2006; Black et al. 2013; Hoddinott et al. 2013; Behrman et al. 2014) and even across generations (Glewwe et al. 2001; Alderman and Behrman 2006; Alderman et al. 2006; Walker et al. 2007; Strauss and Thomas 2008; Stewart et al. 2013; Bourke et al. 2016). Most prior studies have focused on a critical window

under age 2 years, after which stunting is claimed in some influential studies to be irreversible (Victora et al. 2008, 2010). However, recent research suggests that early childhood stunting *is* reversible after age 2 years (Mani 2012; Crookston et al. 2013; Prentice et al. 2013; Schott et al. 2013; Lundeen et al. 2014; Georgiadis et al. 2016; Undurraga et al. 2018).

Here we examine a predictor of child stunting that has received limited attention: birth season. We estimate associations between birth seasons and stunting during the first 11 years of life to assess both the reversibility of stunting after age 2 years and the lasting associations between birth seasons and heights. We use birth seasons as a proxy for predictors of growth faltering, such as poor diet and disease, which interact with birth seasons to influence children's growth. Seasons affect work, migration, food consumption, dietary diversity, fertility, and morbidity from infectious diseases (Behrman and Deolalikar 1989a, 1989b; Moore et al. 1997; Rayco-Solon et al. 2005; Hillbruner and Egan 2008; Torche and Corvalan, 2010; Yamauchi 2012; Osei et al. 2016; Abay and Hirvonen 2017). These effects are more marked in rural societies that rely on farming, foraging and seasonal wage labour. Owing to pre-natal stresses in low-resource settings, foetuses that reach their last stage of pre-natal development during the lean seasons of the year, or infants born during these seasons, are more likely to be small for their gestational ages and possibly stunted in early life (Dorélien 2015, p. 211). We focus on weather-related seasonal stresses, but recognise that some seasonal stresses have cultural origins (Majid 2015).

The study of birth seasons and child stunting will likely gain importance with climate change (Nuñez et al. 2016) because the impact of climate change on inter-annual and intra-annual temperature and rainfall will affect food availabilities and disease burdens (Patz et al. 1996; Altizer et al. 2013), particularly in low-resource settings (Hillbruner and Egan 2008; Wheeler and von Braun 2013). The study of birth seasons and children's stunting also matters because it speaks to the second UN Sustainable Development Goal of improving the health and nutrition of children aged <5 years in low-resource settings (Lim et al. 2016; UN 2017).

Prior studies of birth seasons and child stunting

Prior studies from low-resource settings suggest that children who experience pre-natal development or birth during the lean seasons of the year are more likely to be stunted.

Svefors et al. (2016) undertook a longitudinal study of the relation between stunting and birth seasons among 1054 newborns in rural Bangladesh. They found that, after adjusting for maternal height and schooling, newborns conceived during the pre-monsoon season when food insecurity and diarrhoeal disease peaked had significantly lower HAZ at birth and were more likely to be stunted at age 10 years. They did not estimate the associations between birth seasons and heights for girls and boys separately.

Lokshin and Radyakin (2012) analysed three national health surveys of children aged <3 years in India. They found that infants born during the monsoon season had 0.5 lower HAZ than infants born during the rest of the year. This gap was the same as the difference in HAZ between children of illiterate mothers and children of mothers who had some secondary education. Controlling for attributes of the children, mothers, households and communities, they found that the negative associations between birth during the monsoon season and heights persisted until age 3 years, the maximum age considered in their study. The magnitudes of the negative associations were the same for girls and for boys, but were stronger among rural children than urban children.

Dorélien (2015) used information from the Demographic and Health Surveys for children aged <5 years born from the 1980s until the mid-2000s in 29 Sub-Saharan countries. She pooled girls and boys and analysed separately the relations between birth period and stunting for each country, finding much variation among countries. In Sahelian countries, stunting was least likely to happen among babies born right after the short rainy seasons, but in countries such as Tanzania and Malawi, stunting was more likely to happen among babies born during the rainy seasons before harvest, the time of highest food insecurity. She found that the differences in the probabilities of being stunted between babies born during the worst months (most infant deaths) and the best months (fewest infant deaths) varied among countries, but it was not clear what explained these differences. The differences were negligible in countries such as Senegal, South Africa, Cameroon, and Côte d'Ivoire, but reached over 10 percentage points in countries such as Chad, Congo, Liberia, and Malawi. Except for Benin, Madagascar, Tanzania, and Zambia, birth months no longer bore associations with HAZ after controlling for maternal fixed effects in the remaining 25 countries studied. The associations between birth months and stunting weakened after children reached 2 years of age, but persisted beyond 2 years of age in Mali, Rwanda and Zambia. She did not analyse differences between girls and boys.

Two other studies also found links between birth seasons and child stunting. Kalanda et al. (2005) followed a cohort of 320 babies born from March 1993 until July 1995 in rural Malawi for 1 year. They found that birth during the rainy season predicted stunting at age 1 year, but not at 6 months, consistent with the widespread pattern of declining HAZ among children aged 0.5–1 years in undernourished populations (Victora et al. 2010). Kalanda et al. (2005) did not analyse the links between birth seasons and heights for girls and boys separately. Liu et al. (1998) studied 425 infants born between September 1984 and March 1987 in urban and rural Pakistan. They followed their growth for 24 months and found that birth during the warm dry season predicted stunting, with stronger associations in rural areas, but no differences between girls and boys.

Three conclusions arise from this review. First, there is geographical variation in seasonal effects on child height, yet none of the studies have included Latin America (Pomeroy et al. 2014). Second, much of the literature focuses on the first 2–5 years of life and pays less attention to mid and late childhood. Third, few studies compared the effects of

seasonal stresses on the heights of girls vs boys. Filling this last gap matters because research from the behavioural sciences and human biology provide unclear guidance on what to expect. The associations between birth seasons and growth may differ between sexes, because girls and boys vary in their abilities to adapt to stresses in gestation and early life, with boys showing more vulnerability to environmental stresses than girls (Stinson 1985; Catalano and Bruckner 2006; Catalano et al. 2009; Krenz-Niedbała et al. 2011). Thus, seasonal stressors should have larger adverse effects on the heights of boys than of girls. However, in many low-resource settings parents are thought to invest more in boys than in girls (Rosenzweig and Schultz 1982; Das Gupta 1987; Behrman 1988; Sen 1990; Schultz 1993; King and Mason 2001). Larger parental investments in boys might redress some or all of the adverse effects of seasonal stresses on boys' heights.

Aims

This article draws on a survey undertaken during 2008 in a society of native Amazonians in rural Bolivia (Tsimane') to investigate two main aims: (a) to describe associations between birth seasons and HAZ separately for girls and for boys aged ≤11 years (pre-puberty) and (b) to assess if the associations change during the first 11 years of life. We restrict the analysis to children aged ≤11 years to avoid the biological complexities from pubertal growth (Proos and Gustafson 2012). The mean age of menarche among Tsimane' girls is 12–14 years and the mean age of puberty among Tsimane' boys is ~14 years (Byron 2003; Walker et al. 2006; Hochberg et al. 2011; Hodges-Simeon et al. 2013; Hodges-Simeon et al. 2016). Besides the two main aims, we extend the analysis of anthropometrics and birth seasons to consider the associations between child weights, in addition to child heights, and birth seasons. Although child weights are highly correlated with child heights, weights capture some different anthropometric dimensions than heights. Thus, this extension to include weights allows for fuller understanding of how seasons might influence child anthropometrics.

The setting

Tsimane' are a society of native Amazonians living mainly in the department of Beni, Bolivia (Figure 1). Bolivia's latest census (2012) estimated the Tsimane' population at 16,958 people (INE 2015, p. 29). For subsistence, Tsimane' practice slash-and-burn horticulture, hunting, fishing, and plant foraging. Much of their food comes from their own production. For instance, only 7% of their calories come from purchases in the market (Henrich et al. 2010). However, the Tsimane' traditional diet is being displaced at the margin by foods bought in the market, such as beef, sugar, pasta, salt, lard, vegetable oil, bread, rice, and white flour (Rosinger et al. 2013, p. 55; Zycherman 2013). Tsimane' have traditionally had limited contact with the Bolivian government (Reyes-Garcia et al. 2010) and low levels of monetary income (Undurraga et al. 2016) and schooling (Bauchet et al. 2018; Undurraga et al. 2018).

Child stunting

Tsimane' children are short for their age compared with international standards of the World Health Organisation (WHO), like children in other native Amazonian societies, but are adequate in weight-for-age and weight-for-height, often above WHO medians (Foster et al. 2005; Godoy et al. 2005; Victora et al. 2008). The prevalence of stunting among Tsimane' children aged <9 years has fallen from 2000 (girls =43%; boys =52%) to 2010 (girls =30%; boys =34%) (Zhang et al. 2016) but remains high by WHO standards (Gurven 2012). The improvement probably came from programmes by the government and non-governmental organisations working in the area. The government has increased vaccination campaigns and the construction of water wells and school latrines and non-profit organisations have delivered public health services to Tsimane' villages. In addition, the area has witnessed improvements in socioeconomic conditions. For instance, 2002–2006 saw improvements in adult (aged >16 years) food consumption and body-mass index (BMI) (Godoy et al. 2009b). Despite improvements, the lingering causes of child stunting remain unclear. Some studies found that infections (e.g. helminth), birth order, inadequate protein consumption and maternal weight correlated with child stunting (Gurven 2012; Nyberg et al. 2012; Tanner 2014), but other studies found no correlates of stunting (Foster et al. 2005; McDade et al. 2007) .

Seasons

The study area has two seasons: a rainy season from October until April, and a dry, colder season from May until September (Figures 2 and 3). The transition from the dry to the rainy season takes place during October–November. Unlike other parts of the world with well-defined seasons of hunger and plenty, the study area lacks such extremes. Each season brings benefits and costs, making it hard to predict the effects of seasons on child growth. For instance, seasonal work effort (particularly of pregnant or lactating women) might predict child growth (Rayco-Solon et al. 2005), but among Tsimane' work effort has two peaks: horticultural work peaks during *both* the transitional months of October–November and during the rainy season (February–April) while foraging peaks during *both* the rainy (December) and the dry season (June) (Godoy et al. 2009a).

Dry season

At the onset of the dry season many edible forest fruits ripen, which provide food and contribute to the weight gain of edible wild animals (Huanca 2008; Luz 2012), principally spider monkey, tufted capuchin, collared peccary, red brocket deer, and tapir (Luz 2012, pp. 19–20). During the dry season, Tsimane' hunt more and forage more for feral plants (Godoy et al. 2009a; Luz 2012). In a five-quarter longitudinal study in two villages, Reyes-García (2001) found that households used a total of 49 wild plants as food. Most of these were edible fruits, principally Palmae (e.g. *Bactris gasipaes*), Glusiaceae (e.g. *Rheedia acuminata*), and Moraceae

Figure 1. Map showing 40 villages of the randomised controlled trial (RCT) of village income inequality and health used in this article, department of Beni, Bolivia. Note: The shading of the territory denotes elevation (mamsl = metres above mean sea level). The square symbols and letters in each town are approximately proportional in size to the population of the town. The Tsimane' territory is an administrative division that does not reflect all the lands inhabited by the Tsimane'. The unmarked name 'El Alto' underneath La Paz refers to a sprawling urban settlement abutting the city of La Paz.

(*Pseudolmedia laevis*). She found slightly more dependence on wild plants during November–February and August–November than during the rest of the year. In the same study, Byron (2003) found that wild foods were mentioned infrequently in dietary recalls, probably because wild foods were eaten away from home at the moment they were encountered. During the dry season, Tsimane' take advantage of the up-river fish migration by fishing in groups with plant poison, or by fishing alone with nets, bows, and arrows. The dry season is also the time when road travel to towns and markets is easiest.

On the negative side, the dry season brings surges of intense and sudden cold weather, causing temperatures to drop by as much as 10 °C from one day to the next, with potentially adverse health consequences (Espinoza et al. 2013). Besides having the lowest temperatures of the year, the dry season is also when households' stocks of rice, the principal annual cash and food crop, are lowest (Vadez et al. 2008). Some types of agricultural work (e.g. forest clearing) and male out-migration for temporary wage labour peak during the dry season. Zycherman (2013) found that male out-migration during the dry season increased the work load of women left behind and reduced the amount of animal proteins from wildlife. This happened because men are the primary hunters, so male out-migration reduced the number of hunters in the household.

Rainy season

Tsimane' harvest rice during the rainy season. In the rainy season communication between villages along rivers is
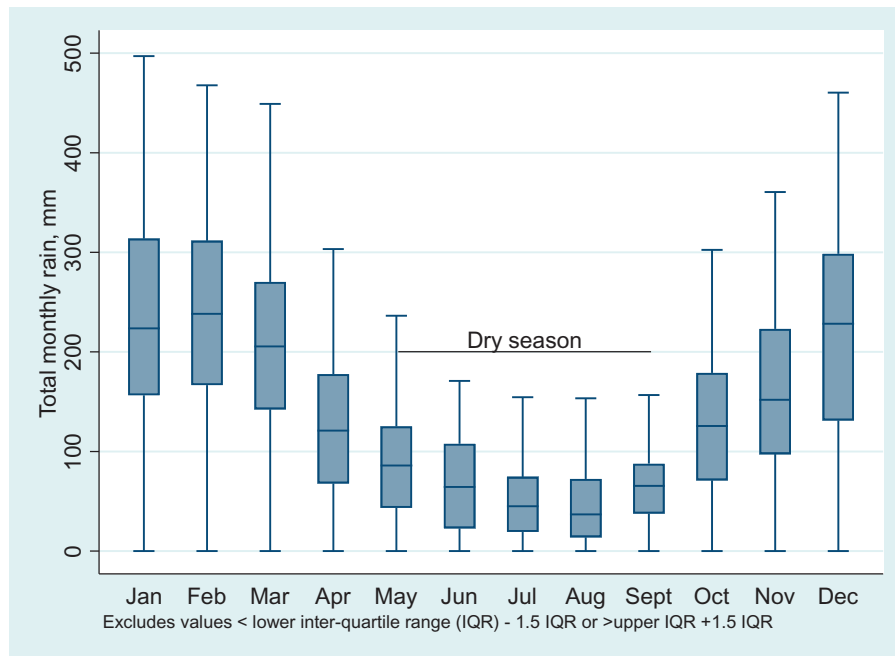
Figure 2. Total monthly rainfall averaged over all years (1943–2013): Town of San Borja, department of Beni, Bolivia. Source: Servicio Nacional de Hidrología y Meteorología de Bolivia (SENAHMI).
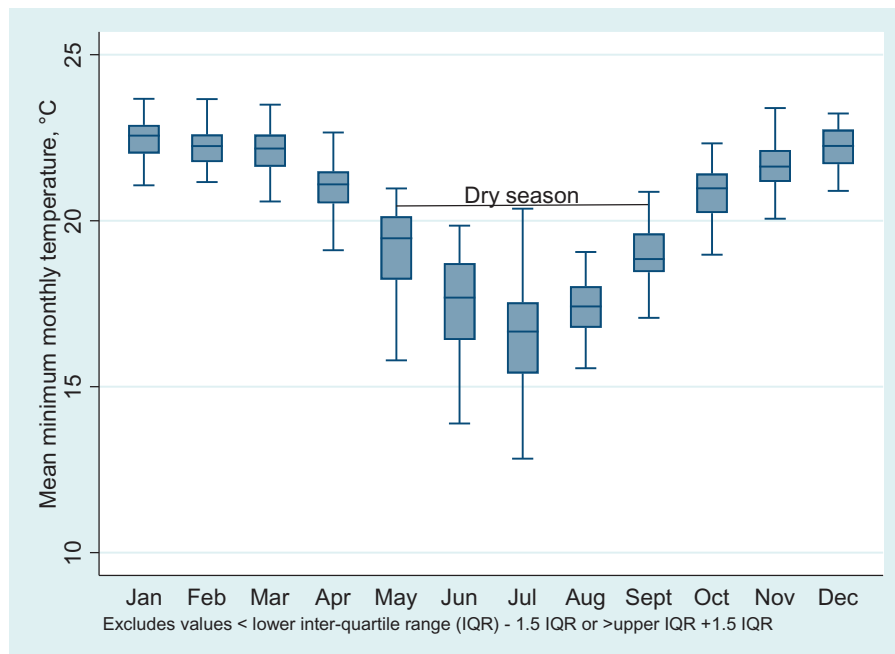

Figure 3. Mean minimum monthly temperature averaged over all years (1962–2013): Town of San Borja, department of Beni, Bolivia. Source: Servicio Nacional de Hidrología y Meteorología de Bolivia (SENAHMI).

easiest. On the negative side, the rainy season is also the time of flooding and most crop losses, and when ground transport between villages and towns is hardest. Parasitic illnesses are more common during the rainy season (Rosinger 2015).

Birth season and human biology among the Tsimane'

Because each season brings benefits and costs, they produce *a priori* unclear net effects on births, child mortality and heights.

Births and child mortality

Based on 1758 records of people from a Catholic mission along the Maniqui River that kept vital statistics, Gurven (2012) found that infants born during some months of the rainy season (January–March) and the dry month of August were more likely to die in the first year of life than infants born during the start of the dry season (May–July) or than infants born during the last month of the dry season (September) and transition to the rainy season (October–November). Undurraga et al. (2015) used

observational annual longitudinal data (2002–2007) from 13 villages along the Maniqui River and found that most births took place during the dry season (May), with higher than average births from March until August, but with a trough in September and with a secondary peak of births in October. Gurven (2012) used vital statistics from the Catholic mission just mentioned and found several peaks in births throughout the year, with two peaks in the dry season (May–June, August) and one peak in the rainy season (March). He also found that the risks of infant mortality were highest for children born during both the rainy season (January and April) and the dry season (August).

Heights

Intra-annual rainfall variability (but not rainfall amount) at the time of conception was associated with lower adult female (but not male) height (Godoy et al. 2008). Zhang et al. (2016) used longitudinal data from 13 villages that were not part of the current study and found that, after controlling for child, maternal, household and village fixed effects, boys aged 2–7 years born during the dry season in 2002 had 0.06 HAZ units/year lower growth during 2002–2010 than boys born during the rest of the year. They found no associations between birth season and HAZ growth for girls.

Diet, breastfeeding, and child food consumption

We next discuss Tsimane' diet, breastfeeding and child food consumption, because they all could attenuate the effects of seasons on child growth.

Diet

The traditional Tsimane' diet consists of rice, manioc and plantains as the main sources of calories, with food from domesticated animals, fish and wild game as the principal sources of animal proteins. Maize occupies a secondary role in the diet. Manioc and plantains are harvested throughout the year, but the other food crops in the Tsimane' diet vary by season (Vadez and Fernández-Llamazare 2014). Rice and maize are harvested once a year, during February–April, but a smaller harvest of maize occurs during the dry season (July–August). Whereas rice is eaten directly, maize and manioc are often used as ingredients in the production of a traditional fermented beverage (*chicha*). Fishing, hunting, and the gathering of wild fruits take place from May until December. Analysis of household-level food consumption suggest that the Tsimane' diet meets daily energy and protein requirements (Zhang et al. 2016), but might be short of key micronutrients. Thus, child stunting probably captures more the effects of infectious diseases and poor quality diet than limited amounts of food (Godoy et al. 2005).

One factor that might help erase differences in food consumption by season is the ubiquitous cultivation of manioc and plantains. Plantain is a perennial crop that produces fruits throughout the year and manioc is an annual crop, but some varieties can remain on the ground for more than a year. These hardy crops tolerate human neglect and environmental insults, do not require commercial inputs, and are easily accessible to any household throughout the year.

Breastfeeding

Breastfeeding is the primary form of infant feeding among Tsimane'. A sample of 1232 survey responses from a 9-year longitudinal study (2002–2004, 2006–2010; 2005 data on lactation duration is missing) suggests that lactating women breastfed an average of 11 months (median $n = 10$; SD $= 8$), with women from older birth cohorts breastfeeding longer. Each additional decade of mother's age was associated with 1.4 more months of breastfeeding. Longitudinal data also shows that lactating women surveyed during 2010 breastfed 3.4 fewer months than lactating women surveyed in 2002.

The decline in the duration of breastfeeding was accompanied by earlier introduction of complementary foods. Veile et al. (2014) studied 80 Tsimane' mother–infant dyads and found that between 2003 and 2011 the mean age when a child was introduced to complementary foods fell by ∼1 month. They also found that the average age when infants were fully weaned was 19.2 (±7.2) months. Complementary feeding was more frequent than breastfeeding at 13.3 months of age.

Child food consumption

Ethnographic observations suggest that household meals are often arranged around a common pot, with adults and children serving themselves or receiving portions from the pot. Older children and adults supplement their household food by snacking on items they encounter as they move through the village and its surroundings (Byron 2003). Breastfeeding among infants and food sharing and snacking among older children may protect them from the effects of seasonal food variability in the household.

Methods

Data for this study come from the baseline (2008) survey of a 2-year (2008–2009) randomised control trial in 40 villages. The trial was designed to assess the impact of in-kind income (food) transfers and changes in village income inequality on individual health (Undurraga et al. 2016). For the current study we use only baseline data, because the trial may have affected seasonal patterns in diets and child nutrition (Undurraga et al. 2016; Saidi et al. 2017). The sample with complete information on child birth date, sex, and HAZ included 562 girls and 546 boys. The methods used to gather data were pilot tested and used during the first 7 years (2002–2007) of a longitudinal study (2002–2010) among Tsimane' (TAPS; Tsimane' Amazonian Panel Study) in an additional 13 villages along the Maniqui River that were not part of this study (Leonard et al. 2015).

Birth dates and ages

Accurate estimates of birth dates and ages are hard to obtain in illiterate, remote societies (Howell 2000; Blurton-Jones 2016). Until recently, Tsimane' did not have birth certificates because they lived in remote areas, often beyond the reach of the national or municipal governments (Reyes-García et al. 2010). To our knowledge, the only Tsimane' community with vital statistics is the Catholic mission along the Maniqui River noted above and studied by Gurven et al. (2007) and Gurven (2012). Low levels of literacy and numeracy (Undurraga et al. 2013, 2018), plus tendencies to round their own or their children's reported ages to multiples of five, add noise to age estimates (Godoy 2017).

We asked parents to report the birth dates of children aged ≤11 years living in their households at the time of the survey. Reported ages are probably more accurate for younger than for older children, since parents would have had to base their estimates on a shorter recall period. To estimate children's ages, we computed the elapsed time from reported birth dates to the dates when we took anthropometric measures.

Heights

We measured the standing heights for children aged ≥2 years following the protocol of Lohman et al. (1988) and using a SECA 213 portable stadiometer. To measure recumbent lengths for children aged <2 years we used the measuring board of the Perspective Enterprise stadiometer (Model PE-AIM-101). We recorded heights in centimetres to one decimal point. From raw height measures we calculated HAZ scores using the WHO standards for children aged ≤60 months (de Onis et al. 2004; WHO 2006) and the WHO standards for children aged >60 months (de Onis et al. 2007). Following the WHO (2009) guidelines, height measures for 65 children in the original data set with height data ($n = 1,585$; 4.10%) and with HAZ measures beyond ±6 were flagged as probably contaminated by large measurement errors and excluded from the analysis.

Weights

Body weights were measured to the nearest 0.2 kg using hanging scales for children aged <2 years and standing scales for children aged ≥2 years. The weight-for-age Z-scores (WAZ) were calculated using the WHO standards for children aged ≤60 months (de Onis et al. 2004; WHO 2006) and the WHO standards for children aged >60 months (de Onis et al. 2007). Following the WHO (2009) guidelines, weight measures for 33 children in the original data set with weight data ($n = 1,395$, 2.37%) and with WAZ measures < -6 and $> +5$ were flagged as probably contaminated by large measurement errors and excluded from the analysis. We did not have data on weights or lengths at birth, so anthropometric information for children aged ≤1 year reflect conditions during the first year of life, in addition to conditions at birth.

Analysis

We describe and try to understand systematic departures of Tsimane' children's heights and weights from international standards. We evaluate both age-dependency and birth-season-dependency of HAZ and WAZ. *A priori*, we cannot expect that the possible departures will behave in a pre-defined simple way (e.g. that they will be linear in age, purely sinusoidal in season). However, a saturated model of pure ANOVA type cannot be used because the data set does not contain enough information for good-quality estimation of a saturated model without regularisation (Bamber and van Santen 1985; Rawlings 1988; Wood 2006). Thus, we use a semi-parametric model that allows for flexible treatment of both age trends and seasonality, but that remains parsimonious. Therefore, to analyse the simultaneous associations of age, birth day (expressed numerically as a position of a day within a year, 1–365) and HAZ, we used a generalised additive model (GAM) (Wood 2006), based on penalised (tensor product) splines.

The model was fitted by penalised likelihood using cross-validation for determination of penalty coefficients. Fitting was stratified on child sex, leading to two separate estimates for girls and boys. For child i, we have:

$$HAZ_i = \beta_0 + s_A(age_i) + s_B(birth\ day_i) + s_I(age_i, birth\ day_i) + \varepsilon_i$$
[Eq. 1]

In equation (1), β_0 is an intercept to be estimated together with the following smooth (functional) terms: $s_A(.), s_B(.), s_I(.)$. s_A and s_B are marginal effects of age and birth day. Ordinary cubic regression spline is used for s_A, while cyclic cubic regression spline is used to correctly enforce annual periodicity for s_B. s_I is a parsimonious interaction of age and birth day and is obtained as a tensor product spline. ε_i is a random error term, the distribution of which is assumed to be approximately Gaussian. We used the same approach to estimate the associations between WAZ and birth seasons for girls and boys of different ages.

Results

Figure 4 shows no clear marked difference between the birth seasons of girls and boys. Girls experienced a slight peak of births during June, while the births of boys peaked in March. Nevertheless, the results of simulation-based chi-squared tests of the null hypothesis that the distribution of the number of births was uniform over the months of a year showed no statistically significant results for girls and boys together ($p = 0.59$), for girls alone ($p = 0.72$) or for boys alone ($p = 0.18$). We also tested the null hypothesis that the birth distributions over the months of a year were the same for boys and for girls and found confirmation for the null hypothesis of no significant sex differences ($p = 0.54$).

Figure 5 plots HAZ against birth days for girls and boys separately, at different ages. Among boys, births during the latter part of the rainy season (March–April) and the first month of the dry season (May) were associated with shorter heights, whereas births toward the start of the rainy season (October–November) were associated with taller heights.
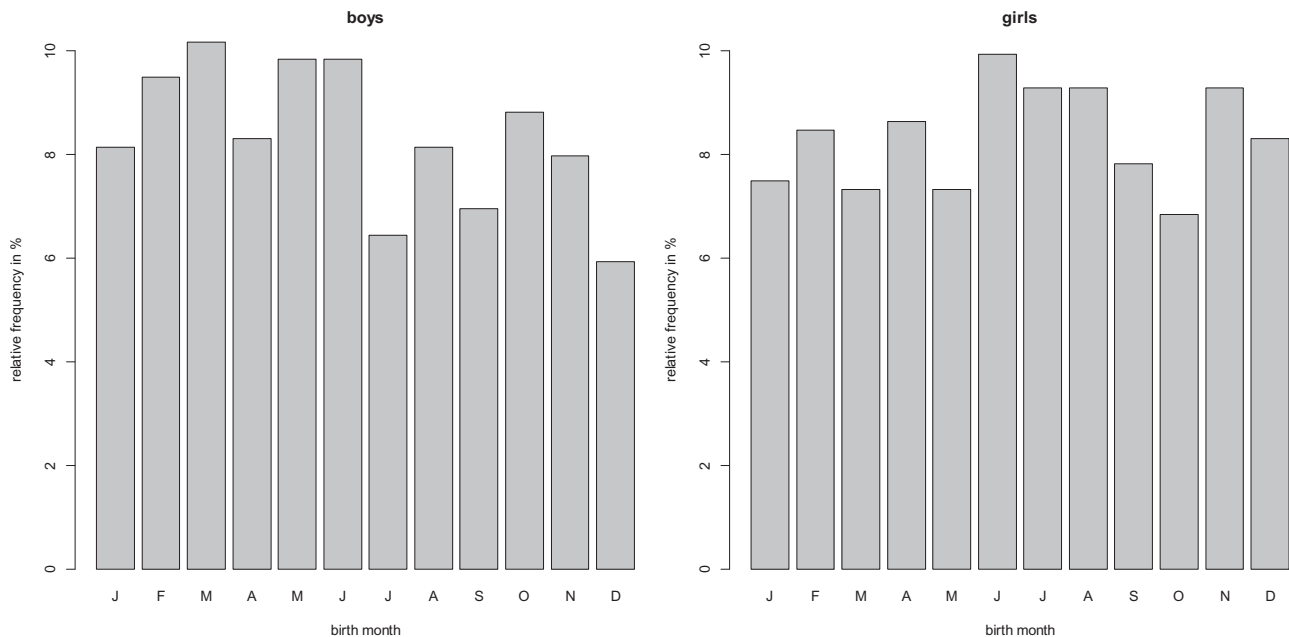
Figure 4. Birth month for Tsimane' girls and boys aged <11 years based on cross-sectional child data collected in 2008.

Stunted boys were more likely than non-stunted boys to be born during the first half of the year and most remained stunted until age ∼5 years. Like boys, girls born during the rainy season (February–April) were shorter, while those born during the start of the rainy season (September–October) were taller than girls born at other times of the year. On average, girls born during the first half of the year were more likely to remain stunted until 5 years of age.

Among girls and boys, ages and birth seasons were associated with HAZ, but the shape (slope) of the associations differed between girls and boys. Taller girls and taller boys were more likely to be born during the last month of the dry season (September) and the first month of the rainy season (October) than during the middle of the rainy season (November–March) or the middle of the dry season (June–July). For either sex, the chances of being stunted were greater if children were born from January until the end of July, with associations between birth seasons and HAZ weakening after 6 years of age. Both sexes showed that, on average, HAZ worsened until 4–5 years of age and improved thereafter. However, the sexes also showed differences. For any given age, the slopes were flatter for girls than for boys, showing that birth seasons had stronger associations with the heights of boys than of girls.

The plots in Figure 5 come from a sex-stratified GAM model, which allows us to perform some formalised inferences. For instance, we can test marginal age and birth-day effects and their (parsimoniously parametrised) interactions. For girls and for boys alike, both marginal terms are statistically significant, while the interactions (parametrised via tensor product spline) are not, as shown in Table 1.

In Figure 6 we show the analogue of Figure 5 for WAZ, again for girls and for boys separately, at different ages. The most noteworthy finding is that birth seasons bore no marked associations with girls' WAZ, whereas among boys we again find that births during the rainy season (particularly March–May) were associated with lower WAZ, while births

during the end of the dry season (September–November) were associated with higher WAZ. A second noteworthy finding is that, during the first year of life, girls and boys have WAZ values that averaged only 0.3 (girls) and 0.4–0.6 (boys) WAZ units below international standards. After the first year of life, WAZ values for girls and boys fall behind international standards, more so for girls than for boys.

Discussion

External validity of previous findings

Our finding that birth seasons correlate with child HAZ among Tsimane' is in keeping with previous studies from Africa and Asia (Liu et al. 1998; Lokshin and Radyakin 2012; Svefors et al. 2016). Some of these studies also found that the associations between birth seasons and HAZ were stronger in poor, disadvantaged (rural) areas (Liu et al. 1998; Lokshin and Radyakin 2012). Rayco-Solon et al. (2005) found that, in rural Gambia, peaks in the prevalence of small-for-gestational-age infants occurred during the end of the rainy season, when food was most limited and maternal workload was highest.

Previous research has shown that Tsimane have low levels of monetary income and schooling and limited saving capacities (Undurraga et al. 2014). Additionally, dependence on subsistence horticulture, foraging, and wage labour might make this a setting in which seasonal fluctuations in weather, food availability, and disease influence childhood growth. Thus, this study supports the hypothesis that associations between birth season and child HAZ are stronger among groups in low-resource settings.

Explaining the links between birth seasons and child HAZ

Until they reach 11 years of age (the maximum age considered in this study), boys and girls born during the rainy
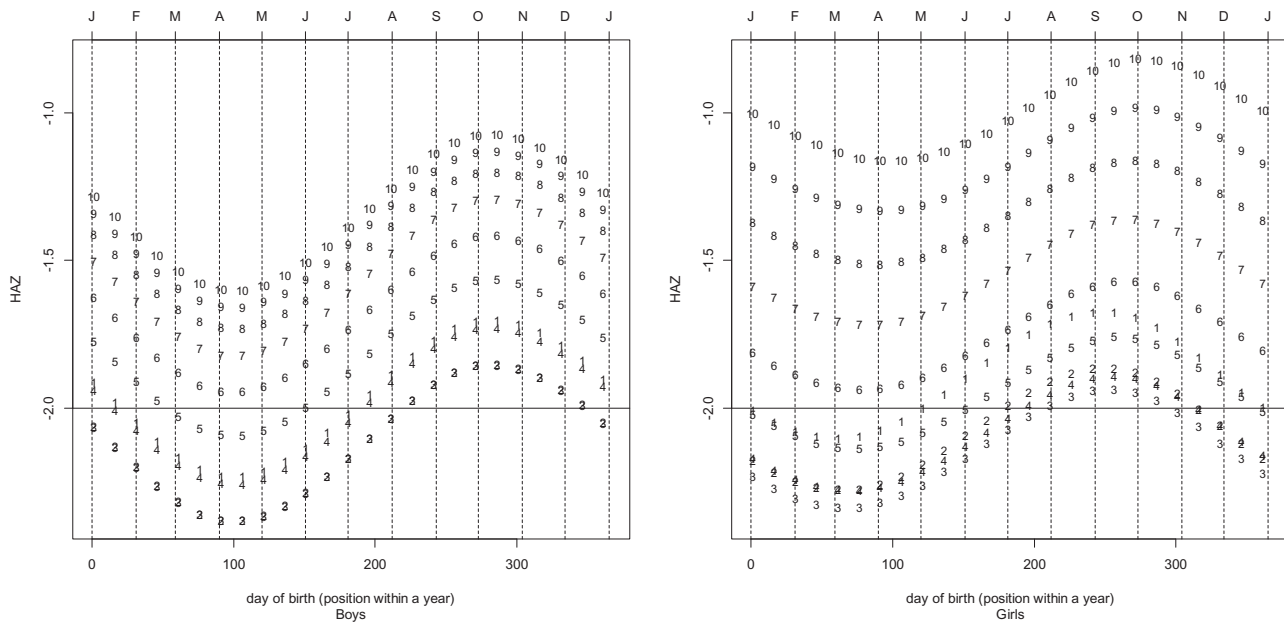
Figure 5. Relation between height-for-age Z-score (HAZ), birth day and age among Tsimane' girls and boys aged <11 years, based on cross-sectional child data collected in 2008. Note: GAM model estimates of the effect of birth day (day's position is numbered 1–365 within a year) and age, obtained for boys and girls separately (model is stratified on sex). Vertical dotted lines denote the beginning of calendar months (January–December). Numbers inside the boxes refer to the age of the child at the time of the 2008 survey. The horizontal line at HAZ = −2 separates stunted (−2 ≤ HAZ) from non-stunted (HAZ > −2) children. Sample size: girls, $n = 562$; boys, $n = 546$.

season (March–May) were shorter than their age–sex peers born during other times of the year. This likely happened because the rainy season was a time of stress for mothers and offspring.

Prior studies of the Tsimane' have documented some of these stresses. Rosinger (2015) found higher water turbidity and higher rates of diarrhoea and dehydration during the rainy season than during the pre-rainy season. Our unpublished analyses of household food consumption show that household energy and protein consumption are lowest during the rainy season, as are measures of dietary adequacy (i.e. energy intake vs predicted requirements) (Appendix). Unfortunately, our data on food consumption comes from household-level surveys that do not allow us to identify the amount or quality of food individual children received and how children's food consumption might vary over the seasons. It is possible that caretakers allocate extra food or higher-quality food to more needy children, as some researchers have reported for other populations in the Amazon (Piperata et al. 2013), the Andes (Leonard and Thomas 1989; Leonard 1991) and Asia (Gittelsohn 1991; Gittelsohn et al. 1997). In our setting there could be differential allocation of food between children across the seasons. All these factors could combine to produce shorter infants, pre-term births or both.

Stresses during the rainy season affected different anthropometric measures of children. Since child heights and child weights were highly correlated (girls, $r = 0.72$; boys, $r = 0.74$) one might have expected seasonal stresses to have adverse associations with both children's heights and children's weights. Seasonal stresses were associated with lower child heights, but did not affect as much weights of children, particularly of girls (Figure 6).

Table 1. p-values for marginal effects and (tensor product spline) interaction in equation (1) and Figure 5.

Effect	Boys	Girls
Marginal effect of birth day within a year	0.001	0.016
Marginal effect of age	< 0.001	< 0.001
Interaction of birth day and age	0.479	0.245

The associations between birth season and HAZ is stronger among boys than among girls

Our finding that the associations between (i) birth seasons and (ii) HAZ (or WAZ) is stronger among boys than among girls is in broad accord with previous studies suggesting that the human biology of boys is more sensitive to environmental stresses in utero and early life than the human biology of girls (Stinson 1985; Catalano and Bruckner 2006; Catalano et al. 2009; Krenz-Niedbala et al. 2011). However note that this means if parents invest more in boys than in girls, as is widely claimed (see references above), these investments are not be sufficient to offset, on average, the boys' biological disadvantages.

Recall from the earlier discussion that few studies have explicitly compared the associations between birth seasons and HAZ for girls and boys. Lokshin and Radyakin (2012) found that—after controlling for many observed and unobserved attributes of child, mother and household—there were no differential effects by 3 years of age, the maximum age in their sample. To compare our results with those of Lokshin and Radyakin, we examine HAZ differentials between girls and boys in several ways. First, to enhance the comparison with the study by Lokshin and Radyakin, we limit the analysis of HAZ differentials between girls and boys for children up to age 3 years. We found that, for the pooled sample of all birth months, boys had significantly lower HAZ than
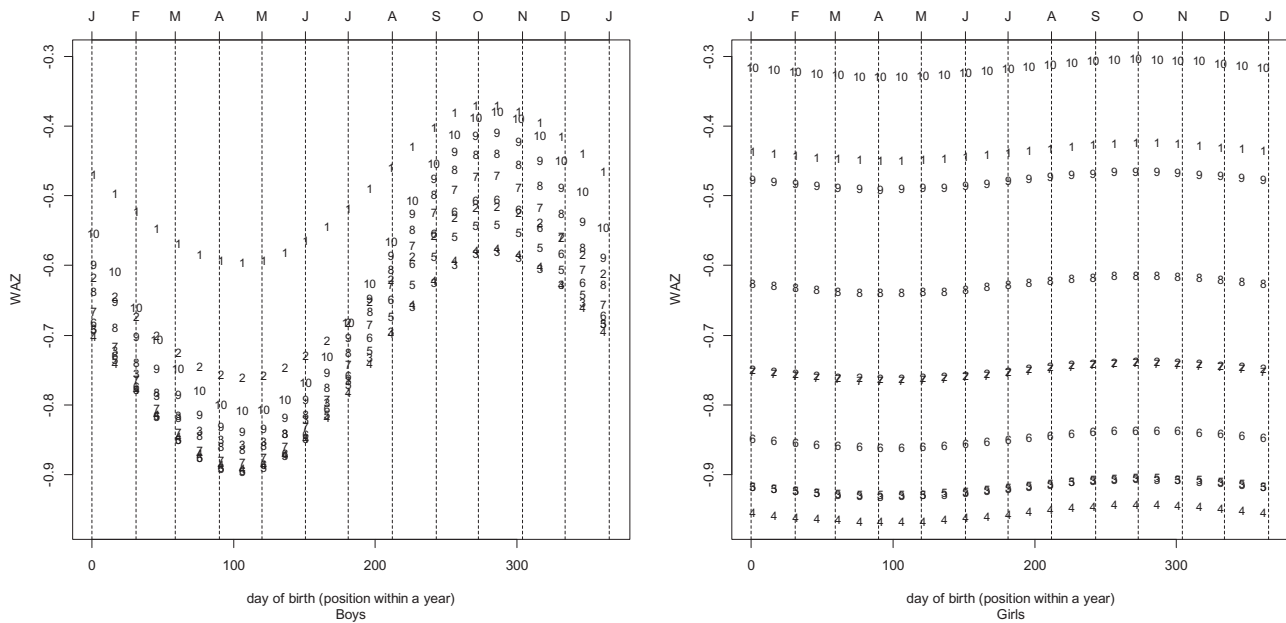
Figure 6. Relation between weight-for-age Z-score (WAZ), birth day and age among Tsimane' girls and boys aged <11 years based on cross-sectional child data collected in 2008. Note: GAM model estimates of the effect of birth day (day's position is numbered 1–365 within a year) and age, obtained for boys and girls separately (model is stratified on sex). Vertical dotted lines denote the beginning of calendar months (January–December). Numbers inside the boxes refer to the age of the child at the time of the 2008 survey. Sample size: girls, $n = 561$; boys, $n = 546$.

girls until 3 years of age ($p = 0.0005$) and that the differences in favour of girls persisted between 3–10 years of age ($p = 0.0002$). However, a test comparing mean HAZ between girls and boys until 3 years of age but restricted to children born during the months associated with taller height (September–October) showed no statistically significant difference in HAZ ($p = 0.542$). If we examine girl–boy HAZ differences in heights for children born during March–April or September–October who were between 3–10 years of age at the time of the survey, we find a difference between the sexes for those born during March–April ($p < 0.0001$), but boys in this age range who were born during September–October had higher HAZ ($p = 0.014$).

Catch-up growth

The fact that, by age 6–11 years, HAZ was generally lower for children born during the first half of the year than for children born during the second half of the year, suggests that the correlations of seasons and heights for girls and boys were not completely erased by late childhood. This finding supports the hypothesis that conditions *in utero* and early life have lasting influences on children's heights. However, our data also suggest that, after a nadir in HAZ reached by age ∼2–5 years, the HAZ of children of both sexes on average gradually improved, with children less likely to be stunted as they aged; by 6 years of age, most girls and boys born during the worst season of the year (first half) had crossed into the non-stunted category. Elsewhere (Zhang et al. 2016), we use the 9-year longitudinal dataset (2002–2010) to show some catch-up growth among Tsimane' children aged ≤11 years. Children stunted at baseline improve by one HAZ unit by age 11 years and had higher annual growth rates than non-stunted children. Despite

some catch up, ∼80% of marginally-stunted children ($-2 \leq$ HAZ ≤ -1) at baseline remained marginally-stunted by 11 years of age. We are aware that the use of changes in HAZ to measure catch-up growth has been contested (Leroy et al. 2015). Nevertheless, the longitudinal information is in accord with the cross-sectional information presented in this article of incomplete catch-up growth.

Explanations for the observed catch-up growth fall into two categories: methodological and substantive. There could be measurement errors related to the timing of measurements and growth spurts. For example, children measured right before early growth spurts would be more likely to appear to recover than children who were measured right after growth spurts.

There are also several possible substantive explanations. First, parents and public programmes might make compensatory investments in food and other resources targeted at children who were stunted in early life, such as happens in other low-resource settings (Wachs et al. 1992). We have no evidence that Tsimane' parents make such compensatory investments, but it remains a theoretical possibility. Second, some villages have seen improvements in water and sanitation infrastructure. Third, after ∼6 years of age children begin to attend school. They are also freer to forage and find additional food outside of the household, so they may begin to become more responsible for their own food and health. Aiello (2013) found that Tsimane' children self-medicated when ill. Fourth, children who had nutritional deficits in early life due, for example, to abnormally bad weather shocks were more likely, on average, to encounter normal conditions when they became older.

Additionally, the pattern we found of stabilisation or improvement in HAZs and WAZs after early childhood is widely observed in the literature on child growth in low-

resource settings (Victora et al. 2010). This pattern partly reflects the fact that absolute rates of growth in stature and weight decline markedly during childhood, compared with growth rates of stature and weight in infancy. Consequently, growth rates track more closely to reference values during childhood than they do during early life (Frisancho and Baker 1970; Leonard et al. 1995).

Faltering in weight gain

In early life, girls and boys start out with WAZ measures only slightly below international medians, but then fall behind, with girls falling behind more than boys. This pattern of declining WAZs during early life is observed throughout the developing world, and is attributable to the combined effects of poor nutrition and high disease loads (Victora et al. 2008, 2010).

Conclusions: policy implications

Our results suggest that redressing stunting requires simultaneous attention to conditions *in utero*, infancy and late childhood. Like other studies in low-resource settings, we too found that birth seasons correlate with child HAZ until pre-puberty. This result supports public health interventions during the first 1000 days of life (conception + first 2 years) (Knudsen et al. 2006; Manacorda et al. 2016). It also supports interventions that reduce the impact of seasonal fluctuations by improving transportation, communication and capital markets that permit better consumption and income smoothing over time. However, our results also suggest payoffs to interventions in later childhood. Although present, the footprint of birth seasons on child HAZ does not lock children into stunting forever. Although they remain shorter than their age–sex peers born at other times of the year, Tsimane' children born during the unfavourable season of the year do converge after 6 years of age towards international median values of HAZ, while not entirely catching-up.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Appendix: Quarterly information on diet among the Tsimane'

Analyses of data on food use comes from five quarterly surveys of 191 Tsimane' households from 13 communities between June 2002 and August 2003. We found significant seasonal variation in energy and protein intakes, dietary adequacy and dietary composition. The dates for the five quarters during which we took measures were:
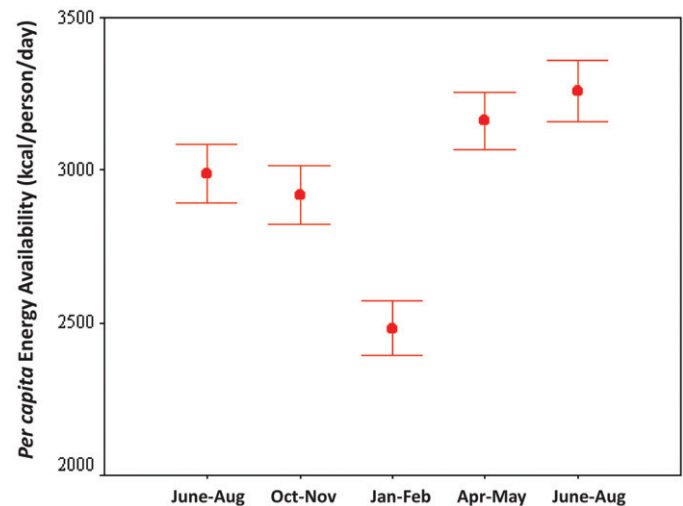

Figure A1. Seasonal changes in *per capita* energy availability (kcal/person/day) in Tsimane' households. The interaction between energy intake and season is statistically significant ($p < 0.001$), with energy consumption being lowest during the wet season (January–February).
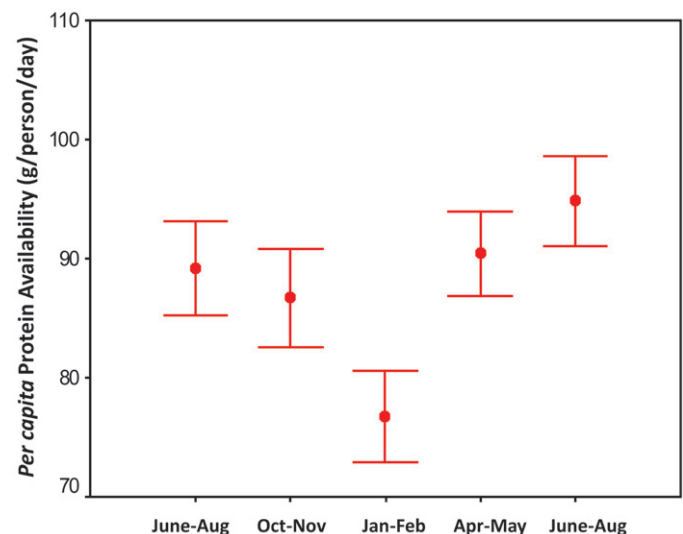

Figure A2. Seasonal changes in *per capita* protein availability (g/person/day) in Tsimane' households. The interaction between energy intake and season is statistically significant ($p < 0.01$), with protein consumption being lowest during the wet season (January–February) …
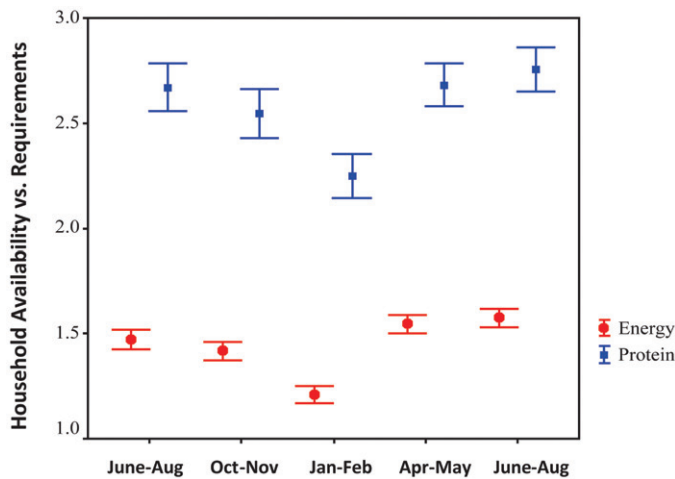
Figure A3. Seasonal changes in household adequacy of energy and protein. Adequacy is measured as the ratio of household availability vs requirements. In Tsimane' households the availability of both energy and protein exceeds predicted requirements in all seasons. There are significant seasonal changes in energy and protein adequacy ($p < 0.01$). Adequacy is lowest in the wet season (January–February).

Q1: June–August 2002
Q2: October–November 2002
Q3: January–February 2003
Q4: April–May 2003
Q5: June–August 2003

Figures A1 and A2 show that per capita energy (kcal/person/day) and protein (g/person/day) availability is lowest during the wet season
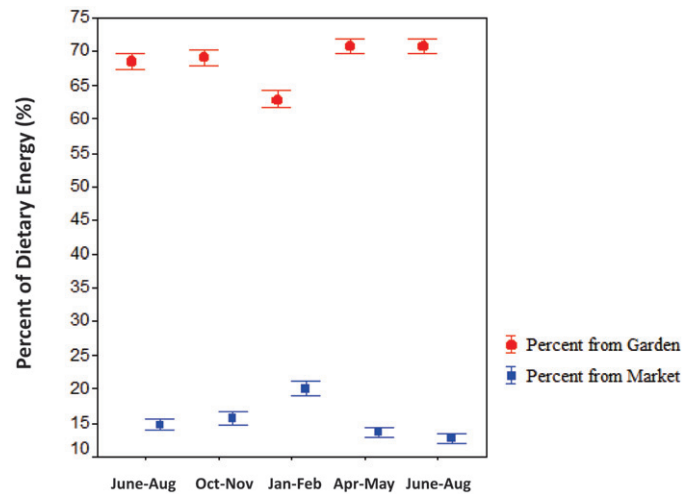

Figure A4. Seasonal changes in the percentage of dietary energy derived from different sources. The percentage of energy from home produced garden foods is lowest during the wet season (January–February), when overall energy availability is poorest. During the wet season, the percentage of energy from market goods is highest.

(January–February 2003), significantly less than in each of the other four seasonal surveys ($p < 0.05$). Similarly, as shown in Figure A3, energy and protein adequacy—measured as the ratios of intakes:requirements—is significantly poorer in the wet season relative to the other four seasonal measures ($p < 0.05$). Finally, Figure A4 shows that, during the wet season, the percentage of household food energy from garden production significantly declines, whereas the contributions of market foods to the diet significantly increases.