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Authors: Shively, Gerald, Smith, Timothy, and Paskey, Megan

Source: Mountain Research and Development, 40(3)

Published By: International Mountain Society

URL: https://doi.org/10.1659/MRD-JOURNAL-D-19-00063.1

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Mountain Research and Development (MRD)
An international, peer-reviewed open access journal
published by the International Mountain Society (IMS)
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Elevation and Child Linear Growth in Nepal

Gerald Shively[1]*, Timothy Smith[1], and Megan Paskey[2]

** Corresponding author: shivelyg@purdue.edu*

[1] Department of Agricultural Economics, Purdue University, 403 West State Street, West Lafayette, IN 47907, USA
[2] Friedman School of Nutrition Science and Policy, Tufts University, 150 Harrison Avenue, Boston, MA 02111, USA

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The relationship between elevation of residence and a child's linear growth was studied using data for 8824 children below the age of 5 years born between 2001 and 2016 at elevations ranging from 50 to 3200 m above sea level in Nepal. Multiple regression was used to measure the role of a variety of household and community factors in explaining the observed elevation effect. A negative association was found between elevation and linear growth that varied substantially across the sample but retained a significant marginal effect across model specifications. Controlling for household wealth, access to markets, indoor air quality, and a range of other factors associated with elevation, for each 1000 m gain in elevation, height for age z score (HAZ) declined by between 0.10 and 0.20 points for an average child, and by between 0.35 and 0.42 points for a child with the characteristics of those living at the highest elevations. Results underscore the potential developmental risks for children living at high elevations and call attention to factors that help to mitigate these risks.

Keywords: *altitude; elevation; anthropometry; nutrition; Nepal.*

Peer-reviewed: *April 2020* ***Accepted:*** *September 2020*

Introduction

Background and motivation

Understanding the role of the physical environment in a child's nutrition, growth, and development is important for targeting public interventions and for assessing trade-offs and synergies associated with potential interventions. In Nepal, where a large percentage of the population lives a kilometer or more above sea level, the topography creates substantial challenges to providing infrastructure, delivering basic services, and improving agriculture. One empirical consequence of these development challenges is a strong observed relationship between elevation and rates of child stunting. High rates of stunting in the mountains is often interpreted as an artifact of factors associated with elevation. In this study, we investigated the relationship between elevation and linear growth directly, using height for age *z* scores (HAZs) for 8824 children below the age of 5 years born between 2001 and 2016 at elevations ranging from 50 to 3200 m above sea level (masl). We focused on HAZ because impaired growth resulting from long-term malnutrition undermines an individual's lifetime health and human capital accumulation, with implications for lifetime earnings and a country's long-term economic development (Almond et al 2018).

We used 3 waves of the Nepal Demographic and Health Survey (DHS). This allowed us to analyze the stature of a large number of children observed between 0 and 5 years of age, a particularly important period in a child's development. Leveraging the richness of the DHS data, we modeled a child's height at a point in time as a function of location, multiple interacting components of socioeconomic status, and health inputs, including exposure to indoor air pollution. This provided us the opportunity to limit the extent to which unobserved socioeconomic status confounds estimates of the magnitude of the relationship between elevation and linear growth. The impact of hypoxia on linear growth is a well-established question of importance in high-elevation studies (see, for example, Frisancho and Baker 1970; Hoff 1974; Frisancho et al 1975; Pawson 1977; Mueller et al 1978). We added to this and more recent literature in 5 important ways. First, although several studies have focused on birth outcomes, the first year of life, and growth among school-aged children, evidence regarding growth between birth and 5 years of age, a truly critical period of child development, remains sparse. Second, relatively few studies of Nepali children have been conducted. Third, a large and detailed database allowed us to perform a more comprehensive analysis than has been previously conducted. Fourth, we explored the impact of hypoxia in conjunction with information on indoor air pollution, a suspected confounder. Fifth, we examined multiple aspects of socioeconomic status, allowing us to more accurately remove many of these effects than has been possible in previous studies.

Related research

Although the terms altitude and elevation are used somewhat interchangeably in the published literature, in this paper we follow McVicar and Körner (2013) and use the term *elevation* to refer to the vertical distance between mean sea level and the point of household residence, rather than *altitude*, which denotes the vertical distance between the land surface and an object not in direct contact with that surface (eg an airplane). In past work, elevation was found to be a significant predictor of linear growth at birth, 6 months, and

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1 year for Bolivian children living at 3600 masl, when compared to their counterparts living at 400 masl. Similar findings were later reported for a different Bolivian sample, as well as for children in the US mountain west and Tibet (Frisancho and Baker 1970; Haas et al 1982; Greksa et al 1985; Dang et al 2007; Zahran et al 2014; Wang et al 2016). Recent research has reinforced these findings in studies similar to ours. Studies using data from high-elevation areas in Tibet (Argnani et al 2008), Argentina (Roman et al 2015), and Ethiopia (Mohammed et al 2020) have shown a negative and statistically significant association between elevation and linear growth, with children living above 2000 masl facing increased odds of stunting of 28–29%, and children living at higher elevations (3000 masl or more) facing even greater risk.

Evidence suggests a possible biological component to these results, including slowed growth of the fetus during pregnancy due to hypoxia (Moore et al 2011). However, some research has shown no growth differences between affluent high-elevation Bolivian children and affluent low-elevation Guatemalan children, suggesting socioeconomic factors could account for the elevation–stunting relationship. Mortality rates are higher in high-elevation ecological zones of Nepal than at lower elevations, and among rural and low-wealth populations (Chin et al 2011), patterns that may be related to stunting and driven by better access to maternal and health services and food markets (Hotchkiss 2001; Chikhungu et al 2014; Mulmi et al 2016).

Among household-level factors that strongly vary with elevation, maternal education stands out as a particularly important predictor of linear growth (Bicego and Boerma 1993; Boyle et al 2006; Semba et al 2008). Similarly, community-level socioeconomic status modifies the effects of household-level socioeconomic status, which suggests that improvements in access to basic community resources may contribute to individual child health (Stinson 1982; Fotso and Kuate-Defo 2005). Recent work from Nepal supports this conjecture. As a number of studies have noted that while nutrition data, measured using HAZ, stunting rates, or other measures have improved for children below age 5 since 2000, gains have been largest for children from wealthier and better educated households (Dorsey et al 2017; Nepali et al 2019; Budhathoki et al 2020; Hanley-Cook et al 2020). In a recent study from Nepal, characteristics of children and households were found to explain most of the variance in height for age and weight for height, with relatively smaller but statistically significant contributions from community-level factors (Smith and Shively 2019). One confounding factor in the elevation–status–stunting chain may be indoor air quality. Evidence from Bangladesh and India indicates that the use of low-quality heating and cooking fuels is strongly and significantly associated with risk of stunting (Hong et al 2006; Mishra and Retherford 2007), and children living at higher elevations may face greater exposure to smoke and respiratory illness due to both household poverty and heating needs.

Methods

Data source and key measurements

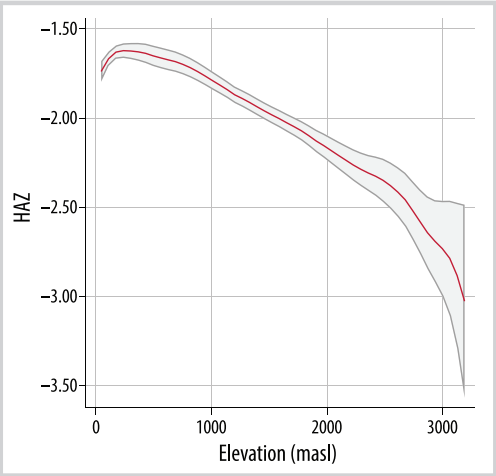
Our data came from the 2006, 2011, and 2016 waves of the Nepal DHS (MOH et al 2007, 2012, 2017). The DHS is a nationally representative household survey, and the dataset combining these 3 waves included 9937 children below age 5. After removing children with incomplete sets of information needed for the analysis (under the assumption that data are missing at random), our final sample included 8824 children residing in locations bounded by 26°37′80.9″N; 80°05′81″E and 28°90′04″N; 88°15′68″E. The DHS sampling methodology for Nepal was consistent over this period. The DHS includes anthropometric data, information on household health, sanitation, and demographic conditions, district-level geographic references, and a community-level measure of elevation. Our observations constituted a pooled cross section of children under 5 years of age measured in a specific survey at a specific point in time. Our outcome variable was height for age *z* score (HAZ), a common measure of long-term nutritional status in children that is calculated by comparing a child's linear growth attainment at a particular age to that of the World Health Organization (WHO) reference population (WHO 1995). We expected the relationship between elevation and linear growth to be potentially nonlinear and mediated through other continuous variables, and therefore we used the continuous measure of HAZ as our dependent variable.

We relied on DHS-reported measurements of elevation, which were available for each survey cluster. This provided a reliable estimate of the elevation a child experienced because these clusters (ie small enumeration units roughly comparable to a community) are sufficiently small such that it is unlikely that a household's elevation would deviate markedly from the community value. We also accounted for several additional household-level factors. We used year fixed effects (for 2006 and 2011, holding 2016 as the reference year) in all regressions. We also included fixed effects for the 3 officially designated agroecological zones of Nepal. The designation of these 3 distinct zones—the Terai, the hills, and the mountains—is based on biophysical and climate characteristics. These vary from tropical in the Terai (17% of land area), through subtropical and cool, but snow-free, in the hills (68% of area), to alpine and seasonally cold in the mountains (15% of land area). These agroecological zone fixed effects are correlated but not collinear with elevation. For example, some hill communities are at higher elevations than low-elevation mountain communities. The designation also reflects economic, cultural, and political circumstances distinct from elevation. The Terai served as the reference zone. Coefficient estimates for these fixed effects are listed in the tables of results and noted as such.

We also included demographic characteristics, including indicators for the gender of the head of the household, child sex, child age with a squared term, urban residency, and several variables capturing aspects of healthcare utilization and sanitation. The DHS provides measures of maternal body mass index (BMI) and education, and a household wealth index constructed by DHS analysts by applying principal components analysis to a set of household assets and characteristics (Filmer and Prichett 2001; see https://dhsprogram.com/topics/wealth-index/Wealth-Index-Construction.cfm). Maternal education can affect childhood health and nutrition directly. It also reflects parental background and earning potential. Similarly, a mother's BMI is a direct measure of her health. In addition, to the extent BMI reflects household food availability, dietary diversity, sanitation, or disease burden, inclusion of maternal BMI in

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FIGURE 1 Height for age *z* score (HAZ) of children below 5 years of age by elevation. Locally weighted scatterplot smoothing (LOWESS) regression line is shown with bands indicating 95% confidence interval. Line plots a running mean least squares regression based on a standard tricube weighting function with a bandwidth of 0.8.



the child's regression controls for these important factors that we cannot observe directly.

Finally, to separate the influence of elevation from that of isolation, we measured remoteness with 2 variables that we added to the DHS dataset: Euclidean distance (in km) to Kathmandu from the centroid of the district in which each child resided, and a quality-weighted measure of road density (in km/km^2) based on Thapa and Shively (2018). These variables are particularly important because accounting for remoteness and isolation independent of elevation in our regressions reduces potential bias in our estimate of the elevation effect that would be introduced by omission of these separate but closely related factors. We have strong reason to believe that infrastructure development supports food security and linear growth for children, particularly in Nepal. For example, Shively (2017) found that additional infrastructure reduces children's vulnerability to negative rainfall shocks, and Shively and Thapa (2016) found that additional infrastructure moderates both the level and volatility of food prices, which matter for food security and dietary quality.

Empirical strategy

We measured the association between HAZ and elevation using unweighted ordinary least squares (OLS) regression models. We did not weight our regressions to match the national population because we were explicitly interested in the heterogeneity of elevation effects between individual children. Because relatively few children live at very high elevations, and because these children represent only about 8% of our sample, the relational importance of high elevation on stunting would be measured less precisely in a weighted regression that implicitly placed more emphasis on low-elevation populations.

While our regressions captured the extent to which the elevation association can be explained by competing hypotheses related to variables correlated with elevation in Nepal, there was one possible shortcoming in our analysis. To the extent family migration decisions systematically coincide with birth timing, our data on growth outcomes could reflect hidden bias due to the spatial sorting of children. In Nepal, internal migration flows tend to run from high to low elevations. As a result, bias in our estimates of elevation effects could arise if migration decisions depend on factors other than those we observed, and if children born at high elevations to nonmigrating mothers are systematically advantaged or disadvantaged compared to children born at lower elevations. According to census figures, the former increased from 9% in 1981 to 15% in 2011, and the latter increased from 7% in 1981 to 10% in 2011 (CBS 2003, 2014). In addition, migrants are primarily male. Furthermore, citing census data, Thapa et al (2019) reported that internal migration in Nepal largely occurs from the hills to the Terai. As a result, we do not expect our regression findings to suffer from a failure to account for endogenous internal migration. However, we acknowledge that international migration, which is also important (Thapa et al 2019), could play a role that we did not account for here. Unfortunately, available data do not allow us to study the migration issue.

Results

Descriptive statistics

We used a pooled dataset combining children from all available years. HAZ values have risen over time in Nepal, but each survey round contains substantial variation in HAZ and elevation. We summarized this variation in Figure 1, in which we plotted a locally weighted scatterplot smoothing (LOWESS) regression line of HAZ against elevation. Figure 1 illustrates the strong negative relationship between HAZ and elevation, although the wide confidence interval at high elevations indicates both a shortage of observations at the highest elevations and the fact that not all high-elevation children have low HAZ. We summarized all variables used in our regressions in Table 1. Table 2 contains a summary and synthesis of the regressions and the main findings. Primary regression results are presented in Table 3, and auxiliary regression results are presented in Tables S1 and S2 (*Supplemental material*, https://doi.org/10.1659/MRD-JOURNAL-D-19-00063.1.S1).

Regression results

We began by fitting a set of baseline models in which HAZ was the dependent variable and elevation was the independent variable of interest. We also included several sets of variables, described below, that may mediate the HAZ–elevation relationship, and a set of control variables, that is, variables that would be expected to correlate with HAZ, and the omission of which from the regression would potentially result in a biased estimate of the marginal effect of elevation. In models 1–3 (Table 3), our independent variables were elevation and our control variables, with no interaction terms. In models 4–8 (Table S1, *Supplemental material*, https://doi.org/10.1659/MRD-JOURNAL-D-19-00063.1.S1), we report regressions that allowed interactions between elevation and controls. In models 9–10 (Table S2, *Supplemental material*, https://doi.org/10.1659/MRD-JOURNAL-D-19-00063.1.S1), we allowed the marginal effect of elevation on HAZ to vary across values of elevation, but we included no interactions. Unless otherwise specified, each control variable entered the model linearly and additively. Our

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TABLE 1 Descriptive statistics for the sample.

Variable	Min.	Mean	Max.	SD
Height for age (*z* score)	−5.96	−1.79	4.99	1.35
Elevation (km above sea level)	0.05	0.79	3.19	0.73
Female child (0/1)	0	0.49	1	0.50
Child age (months)	0	29.8	59.0	17.1
Child age squared (months)	0	1179.0	3481.0	1051.7
Female-headed household (0/1)	0	0.25	1	0.43
Mother: highest education primary (0/1)	0	0.18	1	0.39
Mother: highest education secondary (0/1)	0	0.25	1	0.43
Mother: education beyond secondary (0/1)	0	0.07	1	0.25
Household wealth (index)	−162.4	−17.6	393.2	88.2
Child still breastfeeding (0/1)	0	0.80	1	0.40
Child received vitamin A supplement (0/1)	0	0.79	1	0.41
Child received any vaccination (0/1)	0	0.59	1	0.49
Access to safe water (0/1)	0	0.74	1	0.44
Smoke fuel used in house (0/1)	0	0.84	1	0.37
Urban residence (0/1)	0	0.3	1	0.46
Mother's body mass index (BMI)	14.0	20.8	43.3	2.98
Mother's age at child's birth (years)	13.0	24.7	47.0	5.7
Road density (quality-weighted index in km/km^2)	0	340.6	4408.6	439.6
Euclidean distance to Kathmandu (km)	0	351.1	775.7	203.3
Year: 2006 (0/1)	0	0.53	1	0.50
Year: 2011 (0/1)	0	0.23	1	0.42
Year: 2016 (0/1)	0	0.24	1	0.43
Agroecological zone: Terai (0/1)	0	0.46	1	0.50
Agroecological zone: Hills (0/1)	0	0.40	1	0.49
Agroecological zone: Mountains (0/1)	0	0.14	1	0.35

Note: Min., minimum; max., maximum; SD, standard deviation.

control variables included indicators for year, urban residency, and agroecological zone, and household demographic variables, including individual sex and age (as a level and a square), an indicator for residence in a female-headed household, asset-based wealth index, maternal educational attainment, and mother's age at the time of birth. We also accounted for the presence of health practices that could affect HAZ, including whether the child was currently being breastfed, whether the child had ever received vitamin A supplementation or a vaccination, whether the household had access to clean water, and whether the household used biomass fuel indoors, as well as maternal BMI, as a proxy for short-term calorie availability, diet, and health environment. We also controlled for aspects of remoteness, including the distance to Kathmandu and road density. We treated educational attainment, wealth, maternal BMI, smoke fuel, and the remoteness variables as mediators, and we allowed them to interact with elevation in auxiliary regression specifications. The mediators also entered individually in the models with interactions.

Across all specifications, the estimated coefficient on elevation was negative and statistically different from zero. In terms of magnitude, a 1 km increase in elevation approximately offset the HAZ gain associated with having a mother with secondary education rather than primary education. For example, the coefficient on elevation was −0.219 in model 3 (Table 3), whereas the difference between the coefficients on secondary and primary educational attainments, 0.329 and 0.082, was 0.247. The robustness of the finding on the elevation coefficient to the inclusion of many household controls in model 2, and to the addition of remoteness controls in model 3, was the primary finding of interest in this series of models.

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TABLE 2 Synthesis of findings.

HAZ model	Independent variables	Interactions	Key result	Interpretation	Details
Model 1	Elevation	None	Association between elevation and HAZ is negative and statistically significant (coefficient = −0.277).	For each 1 km increase in elevation, HAZ declines by 0.214–0.277 points; socioeconomic factors such as household wealth, mother's education, and mother's BMI mediate the effect.	Table 2
Model 2	All (see Table 1) except road density and distance to Kathmandu	None	Association between elevation and HAZ is negative and significant (coefficient = −0.214).		
Model 3	All (see Table 1)	None	Association between elevation and HAZ is negative and significant (coefficient = −0.219).		
Model 4	All (see Table 1) plus interactions with education	Elevation × education level	Marginal effect of elevation is robust to the interaction.	Although elevation effects vary over commonly proposed mediators, the elevation results are robust to the combination of additional controls and interaction terms, and the relationship with HAZ remains negative and statistically significant.	Table S1[a)]
Model 5	All (see Table 1) plus interactions with wealth	Elevation × wealth	Marginal effect of elevation loses its significance only at highest levels of the mediator variables.		
Model 6	All (see Table 1) plus interactions with mother's BMI	Elevation × mother's BMI	Marginal effect of elevation loses its significance only at highest levels of the mediator variables.		
Model 7	All (see Table 1) plus interactions with smoke fuel	Elevation × smoke fuel	Marginal effect of elevation is robust to the interaction.		
Model 8	All plus interactions with road density and distance to Kathmandu	Elevation × road density; elevation × distance	Marginal effect of elevation loses significance only at the highest levels of the mediator variables.		
Model 9	All (see Table 1) using a cubic polynomial for elevation	None	Higher elevations disproportionately associated with low HAZ values beyond the linear effect imposed in previous models, but results do not differ significantly from each other or from those in Table S1.	Higher-order coefficients are individually significant, but adding them does not improve the model fit compared with models 4–8.	Table S2[a)]

Note: BMI, body mass index; HAZ, height for age *z* score.
[a)] See *Supplemental material*, https://doi.org/10.1659/MRD-JOURNAL-D-19-00063.1.S1.

The results in Table 3 establish the role of elevation, as its estimated coefficient remained negative, large, and significant across specifications. Because the models summarized in Table S1 (*Supplemental material*, https://doi.org/10.1659/MRD-JOURNAL-D-19-00063.1.S1) included elevation interaction terms, we cannot directly interpret the coefficient on elevation in these regressions as the marginal effect, as the magnitude of elevation's effect on HAZ depended on additional coefficients. Instead, we present in Figures 2–4 the marginal effects of elevation on HAZ, evaluated at different values of the interacting variables. The marginal effect of elevation, its sign, and significance were robust to these changes. In many cases, the marginal effect of elevation on HAZ remained large in absolute value compared to other marginal effects in Table S1 (*Supplemental material*, https://doi.org/10.1659/MRD-JOURNAL-D-19-00063.1.S1). Figures 2 and 3 illustrate that the marginal effect of elevation dropped substantially in absolute value as household wealth and mother's BMI increased. Only at the very highest values of these mediator variables did the marginal effect of elevation lose significance. We saw a similar result regarding road density and distance to Kathmandu: High road density substantially lowered the magnitude of the marginal effect of elevation, although it remained significant throughout almost the entire range of road density (see Figure 4). We interpret these results as evidence that, while elevation effects do vary, in some cases quite substantially, over commonly proposed mediators, they remain robust to the combination of additional controls and

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TABLE 3 Regression results for main models.

	Dependent variable: HAZ		
	Model 1	Model 2	Model 3
Independent variables			
Elevation	−0.277***(0.020)	−0.214***(0.027)	−0.219***(0.028)
Female child		0.030 (0.025)	0.031 (0.025)
Child age		−0.096*** (0.011)	−0.096*** (0.011)
Child age squared		0.001*** (0.0001)	0.001*** (0.0001)
Female-headed household		−0.052* (0.029)	−0.053* (0.029)
Mother: primary education		0.081** (0.036)	0.082** (0.036)
Mother: secondary education		0.332*** (0.037)	0.329*** (0.037)
Mother: above secondary education		0.476*** (0.061)	0.468*** (0.061)
Household wealth		0.002*** (0.0002)	0.002*** (0.0003)
Child still breastfeeding		−0.231*** (0.036)	−0.237*** (0.036)
Child received vitamin A		−0.049 (0.040)	−0.052 (0.040)
Child received any vaccination		−0.072** (0.032)	−0.074** (0.032)
Access to safe water		0.053 (0.033)	0.058* (0.033)
Smoke fuel used in house		0.013 (0.050)	0.011 (0.050)
Urban residence		0.015 (0.033)	0.010 (0.033)
Mother's BMI		0.036*** (0.005)	0.037*** (0.005)
Mother's age at child's birth		−0.005** (0.002)	−0.005** (0.002)
Road density			−0.00001 (0.00003)
Distance to Kathmandu			0.0001* (0.0001)
Constant	−1.569*** (0.021)	4.143*** (1.560)	4.111** (1.600)
Fixed effects			
Year: 2006		−3.526*** (1.045)	−3.518*** (1.066)
Year: 2011		−1.712*** (0.629)	−1.700*** (0.639)
Agroecological zone: Hills		0.124*** (0.043)	0.132*** (0.044)
Agroecological zone: Mountains		0.082 (0.068)	0.077 (0.068)
Observations	8824	8824	8824
R^2	0.02	0.25	0.25
Adjusted R^2	0.02	0.24	0.24

Note: Standard errors of coefficients are shown in parentheses; the reference group (represented by the constant) is the 2016 Terai zone; *$P < 0.1$; **$P < 0.05$; ***$P < 0.01$. BMI, body mass index; HAZ, height for age *z* score.

interaction terms, and the relationship with HAZ remains strong and statistically significant.

In Table S2 (*Supplemental material*, https://doi.org/10.1659/MRD-JOURNAL-D-19-00063.1.S1), we summarize 2 models in which we allowed the strength of the HAZ–elevation relationship to vary across elevation levels. In the first specification, we included a cubic polynomial on elevation, and in the second, we interacted elevation with binary variables taking values of 1 if elevation fell between 1000 and 2000, 2000 and 3000, or above 3000 masl. Results show that higher elevations are disproportionately associated with low HAZ values, beyond the linear trend we imposed in the previous models. However, these model results did not differ significantly from one another or from those summarized in Table S1 (ie *F*-tests failed to reject the null hypothesis of equal variance when comparing these models; see

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FIGURE 2 Average marginal effect of elevation on height for age *z* score (HAZ) of children below 5 years of age, by mother's body mass index (BMI). Vertical bars indicate 95% confidence intervals for marginal effects.

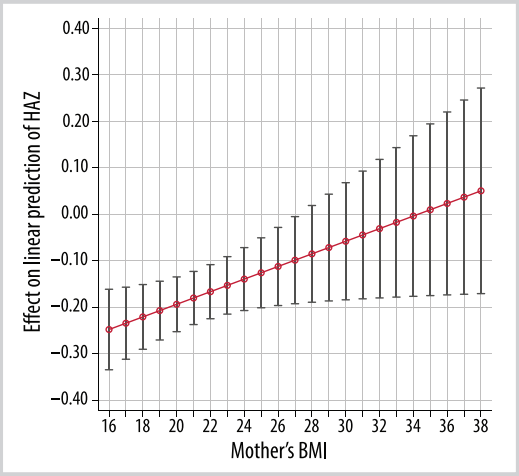


FIGURE 3 Average marginal effect of elevation on height for age *z* score (HAZ) of children below 5 years of age, by household wealth. Vertical bars indicate 95% confidence intervals for marginal effects.

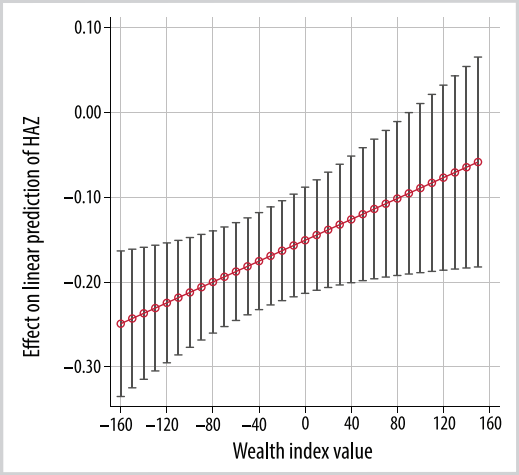
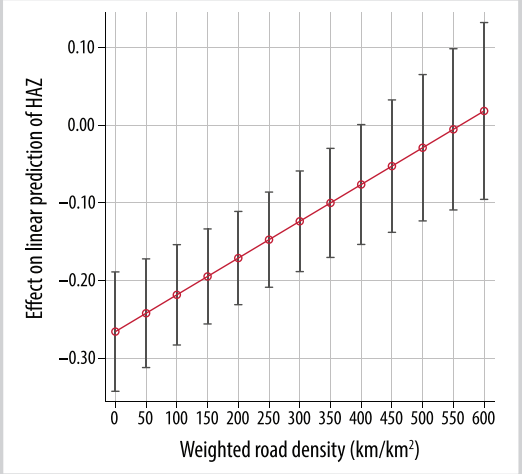


FIGURE 4 Average marginal effect of elevation on height for age *z* score (HAZ) of children below 5 years of age, by road density. Vertical bars indicate 95% confidence interval.



Supplemental material, https://doi.org/10.1659/MRD-JOURNAL-D-19-00063.1.S1). This means that, although the higher-order coefficients are individually significant, adding them jointly does not improve the model fit, indicating that a model that allows a closer nonlinear fit in the relationship between HAZ and elevation does not outperform statistically the linear form assumed in the models of Table S1 (*Supplemental material*, https://doi.org/10.1659/MRD-JOURNAL-D-19-00063.1.S1).

Discussion

Elevation maintained a significant and negative marginal effect across our specifications. In specifications with interaction terms, the average marginal effect maintained a relatively large absolute value. Our investigation focused on the extent to which various mediators or confounders can explain away this relationship: If household and community factors can reduce or remove the elevation effect, one might conclude that elevation does not matter *per se*. As the coefficients on the interaction effects in Table S1 (*Supplemental material*, https://doi.org/10.1659/MRD-JOURNAL-D-19-00063.1.S1) suggest, and as Figures 2–4 show more clearly, household wealth, maternal BMI (a proxy for household food security and dietary diversity), and local infrastructure do alter this relationship substantially. At the very highest values of each of these mediators, the marginal effect of elevation loses its significance, but these figures show that at low (and routinely observed) levels of maternal BMI, wealth, and infrastructure, elevation has a significant and more negative marginal effect on HAZ than at higher values of the mediators. The indoor air pollution coefficients, including the interaction coefficient, were insignificant across all specifications, and therefore for the sake of space, we did not produce figures analogous to Figures 2–4 for those variables. Although previous studies from Nepal have found evidence of indoor pollution affecting stunting (eg Paudel et al 2013), it could be that exposure to indoor air pollution is so ubiquitous across the DHS sample, and such small proportions of households use nonbiomass fuels, that we were unable to detect a pollution–HAZ association. The effect of indoor air pollution may also be captured by wealth or education.

These results underscore the importance of maternal education and socioeconomic status in improving nutritional outcomes. This is consistent with recent work on nutrition in Nepal that included direct measures of healthcare access (Dorsey et al 2017; Nepali et al 2019; Budhathoki et al 2020; Hanley-Cook et al 2020). These studies, which did not account for elevation, nevertheless found strong negative associations between stunting and both maternal education and socioeconomic status. The results on vaccination and breastfeeding are unexpected and at odds with the study of Hanley-Cook et al (2020). The negative correlation observed here between vaccination and linear growth could be a selection problem, wherein children who consume more healthcare do so because they are sicker, but we do not have any evidence from field-level institutional details to say this with confidence. The negative sign for "still breastfeeding" could be an artifact of breastfeeding older children for whom it may not be

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nutritionally helpful, but we lack information to test this conjecture.

To further aid in the interpretation of our findings, we quantified the predicted effects with a thought experiment designed to isolate the elevation effect from other factors. Consider the possibility of moving a hypothetical child from a high-elevation to low-elevation setting while maintaining the household characteristics representative of a typical high-elevation household. To do this, we multiplied a hypothetical change in elevation by marginal effects of elevation in the interaction models summarized in Figures 2–4, evaluated at the mean values of mother's BMI, wealth index, and road density for children in the top and bottom deciles of the elevation distribution. These calculations suggest that, holding all else constant, the HAZ of a child at the 95th percentile of elevation would improve by 0.35–0.42 if relocated to the 5th percentile of elevation while maintaining the characteristics of the high-elevation household. In other words, the effect of a decrease in elevation of approximately 2000 m would result in an improvement in linear growth slightly greater than the improvement associated with having a mother with secondary education versus one with no education. For a somewhat less dramatic example, moving a child from the 90th percentile of elevation to the 50th percentile of elevation, a change of approximately 1200 m, would improve HAZ by 0.22–0.27, an improvement slightly smaller than the gains associated with having a mother with primary education rather than no education. Mean values of wealth and road density are much higher at low elevations than at high elevations, so the implied effects of a move from low to high elevations, maintaining original mediator values, are not symmetric. The wealth and road density interaction models suggest that moving a child to higher elevation—from the 5th percentile to the 95th percentile—would reduce the child's HAZ by 0.29 and 0.18, respectively, and that moving a representative child from the 50th to the 95th percentile of elevation would reduce HAZ by 0.18 and 0.11. The thought experiment of moving from high to low elevation underscores the costs high-elevation children face, but the asymmetry between hypothetical moves highlights the degree to which higher values of mediator variables weaken the elevation effect. This is important because it suggests that improvements in basic indicators of development in mountain settings, for example, in infrastructure and household wealth, could substantially mitigate the high-elevation growth drag for young children.

Elevation is strongly associated with restricted linear growth in particularly remote areas. However, even in places with average values of wealth, maternal BMI, and road density, the marginal effect of elevation (approximately –0.20) is statistically significant and nontrivial in magnitude. This suggests elevation matters on its own, because even the most convincing of the confounders we can add to the model does not eliminate the elevation effect entirely. Although we cannot fully rule out differences in agricultural production and diets as explanations of differences in HAZ across elevations, we believe the inclusion of maternal BMI in our models captures a substantial component of underlying household food access. For unobserved variation in agricultural conditions and food access to negate the elevation finding, the following would be required: (1) wealthier, high maternal BMI, and high-infrastructure households have better access to sufficient food and nutrition; (2) these improvements weaken the penalty imposed by living at high elevations; and (3) this effect absorbs any effect of the mediators it confounds. While our data do not allow testing of these suppositions directly, the first likely holds. We are more skeptical about the second and third, however: Diet enhancements can clearly improve HAZ, but it is not obvious that diets should matter more at high elevations than at low elevations, or that hidden variation in diets could completely account for mediators. Future research for Nepal and elsewhere might attempt to account for dietary factors directly. For example, in a recent study of Ethiopian children living at high elevation, Mohammed et al (2020) found a negative association between height and elevation while controlling for household dietary diversity, measured using 24 hour recall data on 7 food groups. This suggests that the elevation relationship is robust to the inclusion of dietary measures.

Micronutrient deficiencies arising from the micronutrient content of soils at high elevations could also contribute to this relationship, as zinc and iron deficiencies are correlated with stunting (Prasad 1991; Gibson et al 2008; Bevis 2015). Zinc deficiencies in diets can arise due to zinc deficiencies in soils, particularly in places where people rely on their own production and consume limited amounts of animal protein because the zinc content of plants comes directly from the soil in which they grow (Mayer et al 2007; Singh 2009). There is also a growing body of evidence showing that zinc deficiencies can hinder the absorption of iron, so that a zinc deficiency can contribute to iron deficiency, which can also slow growth (Graham et al 2012). In Nepal, soils at high elevations are generally deficient in zinc and iron (Andersen 2007). If soils in the Terai have more iron and zinc than those at higher elevations, children in subsistence households at higher elevations may have higher rates of stunting due to lack of iron and zinc in diets. When households at high elevation in Nepal purchase foods, they are likely purchasing foods grown at lower elevations, and to the extent that soils at lower elevations contain sufficient iron and zinc to support adequate levels in diets, this access to market-provided food could reduce the risk of stunting. Bevis et al (2019) reported evidence that low-zinc soils are associated with elevated rates of stunting in Nepal's Terai. If high-elevation soils are disproportionately prone to zinc deficiencies, this could be playing a role in our findings related to elevation. There is also evidence that boron toxicity, if present, could contribute to slow linear growth for some children living at high elevations (Hjelm et al 2019).

We cannot fully rule out differences in agricultural production and diets as explanations of the differences in HAZ across the range of elevation studied here. As we noted above, maternal BMI may capture a component of household diets, as it is at least partially correlated with underlying food access in the short to medium term. Our inability to measure these factors directly is a limitation. A larger sample of children from the mountain zone, which includes the highest elevations in Nepal, would also improve our study, because these children comprised only 8% of our sample. Many hill-zone children live at elevations similar to mountain-zone children, somewhat reducing this shortcoming. However, having more observations of children in the mountain zone would improve confidence in our findings.

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Last, growth and development under hypoxic conditions could not be observed directly in this study; however, hypoxia has been shown to affect growth in animal models and should be considered as a factor in the linear growth differences observed at elevation. Farahani et al (2007) argued that chronic constant hypoxia (CCH) and chronic intermittent hypoxia (CIH) produce different body and organ growth patterns. In CCH, changes to liver and kidney size are proportionate to body size, while heart, lungs, and brain are spared or increase in size relative to the body. In animals, measurable changes due to hypoxia appear as quickly as 7 days after exposure; individual mice exposed to CIH in the study were able to catch up from the loss of growth, but those under CCH were not (Farahani et al 2007). Additionally, elevation may play a role in hypoxia inducible factor (HIF) signaling, impairing normal development in oxygen delivery tissues (Harrison et al 2015). This suggests that hypoxia-mediated regulation of growth may be an important aspect of normoxic development in all animals, including humans.

Conclusion

Arguments in favor of improving conditions in remote and very high-elevation mountain areas are often dismissed as cost-ineffective due to low population density and difficult access. Further, development funding in Nepal, and elsewhere, often focuses on metrics such as the number of individuals reached per unit of development investment, which can leave the remotest areas further marginalized. Cost-effectiveness is clearly an important consideration whenever budgets are constrained and trade-offs must be made, but often the full spectrum of payoffs from mountain development is not fully appreciated or accounted for. In this paper, we examined the relationship between child growth and elevation in Nepal, with an emphasis on evaluating the extent to which other factors, particularly remoteness, household resources, and indoor air pollution, mediate or explain the observed negative relationship.

We found a pernicious effect of elevation on child growth that was very robust to the inclusion of many variables and consisted of more than mere remoteness. This suggests that elevation is strongly associated with child growth in Nepal, and that some forms of development could help to ameliorate this effect, although defining and validating an exact mechanism that would let us make a credible causal case are outside the scope of this study. In this sample, elevation effects were mediated by household wealth, maternal BMI, and infrastructure. These are all amenable to public interventions. While elevation maintained a negative and significant sign at all but the highest values of road density, the magnitude of this marginal effect dropped substantially as density rose. Improvements in infrastructure provide a strong source of mediation, as even a moderate change in road density resulted in a large change in the marginal effect of elevation. Figure 4 suggests that if all children in our sample, regardless of their elevation, experienced the average road density observed among children in the bottom elevation decile, then those children living at the 90th percentile of elevation (approximately 2000 masl) would exhibit HAZ values approximately 0.25 points higher than those observed at lower elevations given their current levels of road density. At the highest levels of road density, the elevation effect would disappear entirely. The robustness of this HAZ–elevation relationship suggests a role for nutrition interventions specifically targeting children at high elevations, as they face more restricted linear growth than do their lower-elevation cohorts. Importantly, differences did not disappear when we accounted for key potential confounders, including household wealth, remoteness, and indoor air quality. We expect that researchers studying children living in similarly remote communities (as has been documented in, for example, Tibet, Peru, and Bolivia) would find similar patterns, both because economic circumstances in these similarly remote areas are sufficiently comparable, and because our socioeconomic controls reduced the extent to which socioeconomic differences between these locations could drive regression results. Our findings suggest a moderate reduction in linear growth for children at high elevations, and they are consistent with findings reported from other locations, including Tibet (Argnani et al 2008), Argentina (Roman et al 2015), and Ethiopia (Mohammed et al 2020). Future studies that combine samples would strengthen our confidence that elevation, and not unobserved country-specific factors, is driving this pattern.

ACKNOWLEDGMENTS

Financial support for this research was provided by the Feed the Future Innovation Lab for Nutrition, which is funded by the United States Agency for International Development (USAID). USAID provides financial support for the DHS Program, but it had no role in the collection, analysis, or interpretation of the data, and it played no role in the decision to submit the paper for publication. The opinions expressed herein are those of the authors and do not necessarily reflect the views of the sponsoring agency.

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Supplemental material

TABLE S1 Regression results for models 4–8 (with variable interactions).
TABLE S2 Regression results for nonlinear elevation specifications.

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