Infrastructure mitigates the sensitivity of child growth to local agriculture and rainfall in Nepal and Uganda

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This paper investigates linear growth and weight gain among 11,946 children below the age of 5 y in Nepal and Uganda, testing the hypothesis that child growth is sensitive to precipitation during key periods in a child's early life. The paper also tests the importance of the economic and physical environments in which children reside. Outcomes are not completely explained by agricultural performance or the observed characteristics of children or their households. Associations between height-for-age z-score (HAZ) and weight-for-height z-score (WHZ) and rainfall are generally positive, but patterns are heterogeneous. At the mean, an increase of 1 SD in agricultural season rainfall is associated with a 0.05- to 0.25-point higher z-score, which translates into increases of roughly 4–13% for HAZ and 1–7% for WHZ. Nutrition sensitivity to rainfall is greater in Nepal, where rainfall is lower on average and wider ranging, than in Uganda. Health and transport infrastructure help to buffer children from the deleterious nutritional effects of precipitation shortfalls, underscoring the role of broadly based economic development in promoting child nutrition.

agriculture | environment | infrastructure | nutrition | precipitation

Persistent malnutrition among young children severely hinders physical and cognitive development (1) and increases the risk and severity of illness, further deepening malnutrition (2). In recognition of the overall importance of child nutrition to a country's development prospects, finding ways to improve nutrition has been labeled a “quintessential sustainable development goal” (3). Evidence-based policy making in pursuit of this goal requires a better understanding of the mechanisms leading to nutrition improvements. Isolating and clearly identifying causal pathways is an empirical challenge, however, because many potential determinants of child health and nutrition are hidden or covary. In this paper, I confront this challenge by combining a wide range of observed data, including precipitation data, to study patterns of linear growth [height-for-age z-score (HAZ)] and wasting [weight-for-height z-score (WHZ)] among children below the age of 5 y (U5s) in Nepal and Uganda. I measure the magnitude and strength of correlations between anthropometric measurements and precipitation at key stages of early life, taking particular care to distinguish clearly between variation in precipitation within locations and variations between locations. I also control for agricultural performance and market and health infrastructure, and test whether these factors are correlated with growth. I find that greater road density and improved access to health facilities mitigate a child's sensitivity to variations in precipitation.

Nepal and Uganda are emblematic of nutrition shortcomings in South Asia and Sub-Saharan Africa. Demographic and Health Survey (DHS) data show that a very large proportion of U5s suffer from malnutrition: 41% of Nepalese U5s were stunted in 2011 (HAZ < −2.0) and 11% were wasted (WHZ < −2.0). In the same year, 33% of Ugandan U5s were stunted and 5% were wasted. Nepal and Uganda face familiar development challenges, including chronic and widespread food insecurity, poor infrastructure, and weak governance. Nepal's most recent Global Hunger Index (GHI) score is 22.2, placing it 58th of 104 countries ranked in 2015 (4). Population growth, low per-capita investments in agriculture, and food grain deficits contribute to food insecurity (5). Even before the 2015 earthquakes, more than 3.5 million

people in Nepal were food-insecure. Many reside in geographically isolated areas dependent on food aid (6).

Uganda is also among the least well-nourished countries in the world. In 2005, a comprehensive study showed that 6% of Ugandan households were food-insecure and 21% were at risk for food insecurity (7). Uganda's GHI score is 27.6 (75th of 104 countries) (4). Malnutrition accounts for 40% of child deaths (8), and childhood anemia prevalence exceeds 60% (9). Uganda's food situation has been complicated by influxes of refugees and asylum seekers, many of whom cannot produce or purchase food. Although Uganda as a whole does not lack food, the typical Ugandan diet lacks diversity and fails to provide sufficient micro-nutrients (10). Seasonal food insecurity is also a problem (11).

Food entitlements have long been recognized as important to nutrition and health (12, 13). The 2008 and 2013 *Lancet* maternal and child nutrition reviews underscore the additional importance of microlevel factors for child growth, including breastfeeding and intakes of vitamin A, zinc, iron, and folic acid (1, 14). Access to safe water, sanitation, and health information and facilities are key (15), especially because immature gut biota and subclinical enteropathy may be causal factors in undernutrition (16, 17). Poor indoor air quality and maternal tobacco smoking are risk factors in child undernutrition, morbidity, and mortality (18–20). Aflatoxin exposure also contributes to impaired growth (21). At broad scales, war, civil unrest, and drought undermine child nutrition, with consequences for educational attainment (22).

Agricultural capacity, diversity, and performance may be especially important to nutrition where households pursue

Significance

Incorporating agriculture into nutrition policy requires an understanding of how agricultural performance, rainfall, and the economic and physical environments in which children reside relate to linear growth and weight gain. This paper combines anthropometric data from children below the age of 5 y in Nepal and Uganda with rainfall data and other information to measure these connections. Anthropometric outcomes are positively correlated with rainfall prior to birth, during the first year, and during agricultural growing seasons preceding child measurement. High rainfall is found to be deleterious to child growth in some settings. Evidence points to the need for agricultural adaptation to low rainfall, as well as broadly based economic development, including continued investments in health and transport infrastructure, to help improve child nutrition.

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subsistence strategies or are poorly integrated into markets (23). Associations between nutrition outcomes and both crop diversity and specific farm practices, such as production of animal protein or fruits and vegetables, are positive (24, 25), but because production is highly sensitive to weather and the climate characteristics of locations, nutrition outcomes may track environmental variability (26, 27). For example, strong mortality effects from season of birth have been found in The Gambia (28), India (29), Indonesia (30, 31), Mexico (32), Nigeria (33), and Vietnam (34). Problematically, the mechanisms by which weather variation affects a population may be masked by beliefs that drive individuals to adapt and adjust to environmental change, as well as temporal and spatial delays and displacements in effects (35). In addition, environmental conditions potentially influence nutrition via multiple indirect pathways, including food prices (36–39) and market access (40, 41). Because seasonality and climate anomalies can affect a range of interrelated factors, among which are crop performance, prices, labor markets, and disease vectors, empirical analysis must control for time- and location-specific covariates, and also isolate within-location weather variability from more substantial between-location variability. When used alone, standard anthropomorphic datasets are insufficient for this task. Here, I combine data from a range of sources to reduce potential omitted variable bias and to measure the sensitivity of linear growth and weight gain to precipitation during key periods, conditional on birth timing, location, and local situation.

Materials and Methods

Smith and Haddad (42) proposed a model of child nutrition in which growth is driven by fixed and random effects observed at three levels, arranged hierarchically: (i) immediate determinants (food intake and health status), (ii) underlying determinants (household food security and health access), and (iii) basic determinants (physical, cultural, and institutional features of communities and nations). Accordingly, I connect two standard growth indicators for U5s to a range of factors aligned along the health and nutrition pathways at different levels. HAZ reflects the impacts of early life events and the accumulation of health and nutrition inputs over time; WHZ is more sensitive to recent consumption and health (43, 44). These z-scores measure dispersions in growth and are calculated as $Z_i = (x_i - \bar{x})/\sigma_x$, where x_i is the individual observation and $\bar{x}$ and σ_x are the median and SD of the WHO's reference population (45).

Nationally representative HAZ and WHZ data come from the 2006 and 2011 DHSs administered in Nepal and Uganda. These DHSs provide 11,946 observations on U5s (7,572 in Nepal, 4,374 in Uganda). The DHS includes detailed information about children, their mothers, and their households. Basic determinants potentially include local weather anomalies and climate characteristics of locations, and must be accounted for to obtain reliable estimates of other relationships. I therefore supplement the DHS with data from other sources, matching information using latitude, longitude, and calendar dates, or, where such matching is not possible or appropriate, by date and district or DHS cluster. These data include historic and contemporaneous monthly precipitation and temperature (Figs. S1–S3), variables from World Bank Living Standard Measurement Surveys, and other public data. The data, their sources, and matching procedures are described in *SI Materials and Methods*. No institutional review board approval was required; anonymized personal data were previously collected with informed consent.

I estimate linear regressions and multilevel (mixed-effects) regressions of the form:

$$Z_i = \beta_{0j} + \beta_{1j}X_{ij} + e_{ij},$$

$$\beta_{0j} = \gamma_{00} + \gamma_{01}W_j + u_{0j},$$

$$\beta_{1j} = \gamma_{10} + \gamma_{11}W_j + u_{1j},$$

where Z_i is the HAZ or WHZ of the i th child (the level-1 unit), X denotes variables observed at the child level, and W represents variables to account for higher level variance. The j subscripts indicate that separate level-1 regressions are estimated for each level- j unit. The expanded variance terms allow one to account for variance arising at multiple levels. For empirical estimation, I extend the nesting to include households, districts, and regions.

Results

Fig. 1 places nutrition outcomes in an overall development context by displaying the bivariate relationships between basic living conditions and child growth in Nepal and Uganda. Each x axis measures the district-level Human Development Index (HDI) in an initial period (2001 for Nepal, 2003 for Uganda); y axes measure subsequent district-average nutrition outcomes in 2006 and 2011 (5 and 10 y later for Nepal, 3 and 8 y later for Uganda). The HDI is an indicator of basic living conditions, constructed as the weighted average of health (life expectancy), education (mean years of schooling), and income (per capita purchasing power parity). The z-score averages are unweighted, but applying population weights does not alter the basic shapes of the figures. Fig. 1 shows that initial conditions are positively correlated with subsequent nutrition outcomes and illustrates that the gains in child growth that have accompanied HDI improvements are especially pronounced for Uganda at a low HDI, and flatten out at a high HDI. In this sense, Uganda's curves bear a striking resemblance to Preston's curves for per capita income and life expectancy (46). Fig. 1 also shows that z-scores have increased in both countries over time, but patterns differ: At the highest HDI values, HAZs have diverged in Nepal, suggesting proportionately larger nutrition gains in high-HDI districts. Uganda displays the opposite pattern: The largest gains in linear growth occurred in low-HDI districts, suggesting convergence of outcomes. In sum, higher levels of literacy, basic health, and economic well-being are associated with nutrition improvements over time, but with a lag: Nutrition gains were greater after a decade than after 3–5 y.

Fig. 2 displays district-level bivariate relationships for several potential drivers of HDI in Nepal, among which are crop yield (median = 2,862 kg/ha; $r = 0.39$, $P < 0.01$), extent of agricultural commercialization (mean = 42% of households; $r = 0.24$, $P < 0.05$), distance to market (median = 192 min; $r = -0.24$, $P < 0.05$), distance to hospital (median = 771 min; $r = -0.29$, $P < 0.01$), improved sanitation in the district (mean = 11% of villages open-defecation-free; $r = 0.20$, $P < 0.10$), density of health infrastructure (mean = 0.95 facilities per 100,000 persons; $r = 0.14$, $P < 0.25$), and road density (mean = 0.20 km/km²; $r = 0.52$, $P < 0.01$). Although all factors are important, assigning independent causality to any single one is problematic: They tend to move and work in concert.

Focusing on agriculture, the idea that consumption tracks production, and therefore that favorable agricultural performance will lead to desirable nutritional performance, is attractive. Table 1

Fig. 1. District-level human development indicators and district-level nutrition outcomes in Nepal and Uganda.

Fig. 2. District-level HDI (2014) and district-level development indicators (2010) in Nepal. Crop yield is measured as the total quantity of district agricultural production in kilograms divided by total planted area in hectares; agricultural commercialization is the percentage of households in the district selling crops and/or livestock; distance to market is the average distance to a *haat bazaar* (open-air market) in minutes by foot; distance to hospital is the average distance to a hospital in minutes by foot; improved sanitation represents the percentage of villages declared open-defecation-free by the government of Nepal; the intensity of health infrastructure is defined as the number of health facilities (clinics and hospitals) per 100,000 persons; and road density is measured as the total number kilometers of earthen, gravel, or sealed roads per square kilometer.

compares district-level agriculture and nutrition performance in Nepal and Uganda. Districts are assigned to one of four categories depending on whether they exhibit yields for the main staple in the district that are above or below the median for all districts, and whether they exhibit above- or below-average z-scores. Observations in the upper left and lower right cells of Table 1 are consistent with a view that favorable agricultural performance accompanies desirable nutritional outcomes. Roughly two-thirds of districts conform to this pattern in Nepal (for HAZ) and Uganda (for WHZ). However, a substantial proportion of districts do not conform: 28% of Nepalese districts and 27% of Ugandan districts are positive deviants for WHZ (above-average nutrition outcomes accompany subpar agricultural performance). Furthermore, 17% and 20% are negative deviants (poor nutrition but strong agricultural performance). These patterns are robust to a change in data (2006 in place of 2011, rural districts only) or variables (medians instead of averages, proteins or starches in place of grains, kilograms per person in place of kilograms per hectare). Of course, district-average agricultural yield may not be the best indicator of average household food security in a district, in part, because productivity is unlikely to be decisive where diets lack diversity or essential nutrients. Nevertheless, the fact that a nonnegligible proportion of districts are found in the off-diagonal cells of Table 1 suggests that other factors may augment and offset the agriculture–nutrition relationship. For example, Nepal and Uganda have been the focus of multiple development projects. These projects could have had differential effects across locations and over time that are correlated with nutrition drivers and outcomes in ways that cannot be easily identified or accounted for in data.

A further complication is that weather in the form of temperature and precipitation differs across locations and time. Measuring the influence of spatial variations in temperature or wetness on nutrition poses serious identification challenges, in

part, because both may influence human health and crop growth in potentially confounding ways, and through channels that may respond to or codetermine nutrition. For example, although adequate rainfall tends to be good for crops, agricultural productivity is not uniformly responsive to variation in precipitation; some regions and some periods of the crop cycle suffer from excessive rainfall, and others from insufficient rainfall. Even where a high amount of rainfall might favor agriculture, it may undermine child health due to water-borne disease transmission. Moreover, to uncover local effects, one must isolate within-location weather variability from between-location variability, which tends to be much larger. Fig. 3 isolates weather variability for rainfall by plotting standardized local rainfall anomalies against the explained portion of short-term child growth. These local associations are particularly heterogeneous and nonlinear in Nepal. In the Terai, WHZ moves strongly in concert with growing season rainfall. In contrast, weight gain in the mountains is especially sensitive to departures from the local norm. Overall, linear regressions for Nepal (Table S2) suggest positive correlations, on average, between growing season rainfall (while in utero, during the year of birth, and preceding the survey year) and HAZ and WHZ. These results hold up to the inclusion of fixed effects for birth year, birth month, and location. Patterns in Uganda (Table S3) are less definitive when birth month, birth year, and location fixed effects are included as regressors, but they do point to a positive correlation between HAZ and growing season rainfall during the birth year. In terms of magnitudes, increases of 1 SD in agricultural season rainfall (110 mm in Nepal, 135 mm in Uganda) are associated with 0.05- to 0.25-point higher z-scores at the mean (increases of roughly 4–13% for HAZ and 1–7% for WHZ). Nutrition sensitivity to rainfall is greater in Nepal, where growing season rainfall is lower on average (mean = 281 mm) and wider ranging (minimum = 15 mm, maximum = 837 mm), than in Uganda (mean = 455 mm; minimum = 222, maximum = 1,022 mm). The cluster-level correlation between WHZ and contemporaneous rainfall is negative for rural U5s in Uganda, a pattern that could be driven by the pernicious effects of rainfall on diarrheal or other diseases. As evidence, Fig. 4 plots the explained portion of WHZ against contemporaneous rainfall anomalies (locally standardized) for three Ugandan groups: urban U5s, rural U5s who presented with diarrhea during the 2 wk before measurement (27% of the rural sample), and rural U5s who did not. Urban U5s appear to be buffered from high rainfall, but positive rainfall anomalies are associated with lower WHZ, especially for rural U5s with diarrhea. Nearly the same pattern arises when a fever indicator (45% of rural U5s) replaces the diarrhea indicator.

To gauge the importance of environmental conditions to child growth, [Table S4](#) provides results for multilevel regressions estimated with children nested within households, households

Table 1. District-level HAZ, WHZ, and crop yields in Nepal and Uganda

Indicator	Crop yield in Nepal		Crop yield in Uganda	
	Below average, %	Above average, %	Below average, %	Above average, %
HAZ				
Below average	35	17	25	20
Above average	18	31	48	7
WHZ				
Below average	25	25	46	4
Above average	28	22	27	23

HAZ and WHZ were computed from unweighted 2011 DHS data. Yields were computed from the 2010 Nepal Living Standards Survey (75 districts) and 2010 Uganda National Household Survey (56 districts).

Fig. 3. Growing season rainfall in year of birth and WHZ for Nepalese children 0–60 mo of age in 2001–2011 (locally weighted regression plots, $n = 4,561$). Values of WHZ used in the figure are predictions from an ordinary least-squares (OLS) regression that includes child- and household-level covariates as well as control variables for location and birth month (Table S1). Values on the x axis are growing season rainfall anomalies in the child's year of birth, standardized by the local mean and SD of rainfall. Standardization is based on rainfall observed over 15 y (1998–2012) at the closest rainfall reporting station ($n = 276$) to the child. Details are provided in *SI Materials and Methods*.

nested within districts, and districts nested within regions. The child-level components of the regressions contain the child, the mother, and household control variables; for Table S4, the upper-level random-effect components are naive regressions with no predictors. Table S5 summarizes the results. The first part of Table S5 contains intraclass correlation coefficients (ICCs). The second part of Table S5 contains variance shares for each level. Although the ICCs are relatively small for upper levels, even modest amounts of intraclass correlation suggest similar treatments or outcomes within groups, underscoring the importance of direct or indirect interventions targeted at households, districts, or regions. Approximately 15–20% of total z-score variance (75–80% of explained variance) occurs at the household level, with relatively modest shares at higher aggregation. After controlling for child- and household-level observables, differences across children within households are far smaller than differences across children at district or regional levels.

Variance shares in Table S5 are similar when administrative regions are replaced by agroecological zones or sample clusters. In other words, suprahousehold group effects are important, perhaps due to spatial spillovers in markets or health provisioning. Support for this conjecture comes from reestimating the WHZ regression as a two-level model (child and district), adding rainfall before the survey and birth month fixed effects, while, at the same time, incorporating district-level variables for road density (kilometers per square kilometer) and median distance to the nearest health facility (minutes by foot). The first two columns of Table S6 indicate that roads and health facilities are both statistically important in explaining district-level variance in WHZ. When included as fixed factors at the child level, they are positively correlated with WHZ and unambiguously reduce the importance of precipitation: The magnitude of the point estimate on rainfall falls by roughly one-third, and the statistical significance of the coefficient declines.

To address the potential importance of temperature as an additional driver of agriculture and health, and hence nutrition, the final two columns of Table S6 report regression results for Nepal that incorporate both temperature and precipitation anomalies. For Nepal, local temperature anomalies over the period covered by the DHS were generally positive, and tended to be larger in 2011 than in 2006. Additional research is required to ascertain the relationship between temperature and child growth. However, inclusion of the temperature anomaly as a regressor reduces the statistical significance of the rainfall variable, leaving signs and magnitudes of other point estimates unchanged. Evidence also indicates a positive contemporaneous nutrition association with the combination of rainfall and temperature (as an interaction), underscoring the likely importance of the agriculture/nutrition pathway for child growth.

High collinearity among variables precludes including a large complement of district-level regressors in these models. Instead, factors operating at higher levels are elucidated for Nepal in Table 2. The entries are constructed by first assigning all HAZ and WHZ observations to their respective quintiles and then summarizing associated district-level data on rainfall, altitude, and five indicators of public investment: roads, health facilities, clean water, markets, and public grain storage. Average growing-season rainfall increases across the HAZ and WHZ quintiles. Average altitude decreases with HAZ and increases with WHZ. In terms of the five infrastructure variables, isolation is negatively correlated with linear growth and weight gain. With few exceptions, children in higher growth quintiles are found in districts with greater road and health facility densities, better water sources, more proximate agricultural markets, and greater public grain storage capacity. Patterns are strongest for HAZ, echoing Fig. 1, where overall development was seen to magnify nutrition improvements over time. Intrinsic to sharp gains in linear growth are greater clinic density (22% higher in the top HAZ quintile vs. the bottom quintile), food storage capacity (41% higher), road density (58% higher), and nearness to

Fig. 4. WHZ for Ugandan U5s (measured in 2006 and 2011) and average annual rainfall in household cluster (locally weighted regression plots, $n = 4,374$). Values of WHZ are the predictions from an OLS regression that includes child- and household-level covariates as well as control variables for location and season of birth (Table S1). Values on the x axis are rainfall anomalies observed in the month of anthropometric measurement, standardized by the local mean and SD of rainfall. Standardization is based on rainfall observed over 34 y (1981–2014) for the sample clusters matched to the CHIRPS dataset ($n = 560$). Details are provided in *SI Materials and Methods*.

infrastructure to buffer exposure, and institutional strengthening to maintain and sustain investments over time. The findings of this study underscore the need to maintain a holistic approach to combating child malnutrition.

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