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Original Contribution

Annual Crop-Yield Variation, Child Survival, and Nutrition Among Subsistence Farmers in Burkina Faso

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Whether year-to-year variation in crop yields affects the nutrition, health, and survival of subsistence-farming populations is relevant to the understanding of the potential impacts of climate change. However, the empirical evidence is limited. We examined the associations of child survival with interannual variation in food crop yield and middle-upper arm circumference (MUAC) in a subsistence-farming population of rural Burkina Faso. The study was of 44,616 children aged <5 years included in the Nouna Health and Demographic Surveillance System, 1992–2012, whose survival was analyzed in relation to the food crop yield in the year of birth (which ranged from 65% to 120% of the period average) and, for a subset of 16,698 children, to MUAC, using shared-frailty Cox proportional hazards models. Survival was appreciably worse in children born in years with low yield (full-adjustment hazard ratio = 1.11 (95% confidence interval: 1.02, 1.20) for a 90th- to 10th-centile decrease in annual crop yield) and in children with small MUAC (hazard ratio = 2.72 (95% confidence interval: 2.15, 3.44) for a 90th- to 10th-centile decrease in MUAC). These results suggest an adverse impact of variations in crop yields, which could increase under climate change.

agriculture; child mortality; climate change; edible grain; food; malnutrition; survival; undernutrition

Abbreviations: CI, confidence interval; FCPI, food crop productivity index; HDSS, Health and Demographic Surveillance System; MUAC, middle-upper arm circumference.

Year-to-year variation in crop yields has potentially important implications for the nutrition, health, and survival of people in subsistence-farming populations (1–3). In areas reliant on rain-fed agriculture, such as rural West Africa, the magnitude of these implications may further rise with increased variability in weather and crop yields, as projected under climate change (4).

However, empirical evidence on the associations of survival and nutritional outcomes with crop-yield variability is limited. A recent review concluded that current evidence on nutritional impacts of crop-yield variability draws on a small number of heterogeneous and methodologically limited studies based on secondary data (2). Most studies on the association of crop yield (or its markers) with measures of undernutrition are cross-sectional (5–9), which limits conclusions about the causality of the association and understanding of the impacts of interannual yield variation (2).

A small number of studies have examined the link between proxies of crop-yield variation and survival—for example, studies of the association of mortality with a measure of household food security (based on agricultural yield) in Tanzania (10) and with spatial variability of the normalized difference vegetation index (a measure of the intensity of vegetation cover) in the year of child's birth in Burkina Faso and Mali (11).

In our study, we examined associations of child survival over the first 5 years of life, nutritional status as measured by middle-upper arm circumference (MUAC), and interannual food-crop yield variation in a subsistence-farming population in rural Burkina Faso, using large, longitudinal data sets. Our main focus was on the associations of child survival with: 1) variation in annual food crop yield in the year of child's birth and 2) with MUAC. In addition, we examined whether MUAC (as an outcome) was associated with crop-yield variation to explore whether the association of child survival with

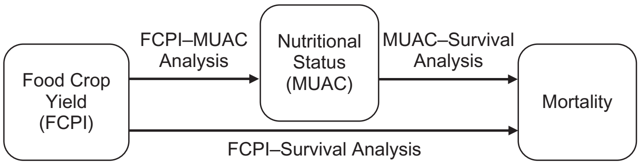

Figure 1. A conceptual map of the associations between food crop yield, nutritional status, and mortality examined in this paper. FCPI, food crop productivity index; MUAC, middle-upper arm circumference.

crop yield is likely to operate through changes in nutrition (Figure 1).

METHODS

Study area and population

This study was based on follow-up of children in the population of the Nouna Health and Demographic Surveillance System (HDSS) run by the Centre de Recherche en Santé de Nouna. The Nouna HDSS area covers one-third of the Kossi province, an area of dry orchard savannah in western Burkina Faso. The single agricultural production season lasts during the rainy season with sowing starting in May/June and the crop harvest in September (12). The local population (297,183 in 2009) is made up almost exclusively of subsistence farmers relying on rain-fed agriculture, with their livelihoods being susceptible to variations in rainfall (12–14).

Mortality/survival. The study of survival was based on data for 44,616 children less than 5 years of age, who were included in Nouna HDSS routine data collection for the period of 1992–2012. During this period, children were followed for vital events and migration every 3 months until 2006 and every 4 months thereafter. We obtained dates of birth and death or in- or outmigration. Individuals born before the start of the study period or outside the Nouna HDSS area were excluded from analysis, as were the individuals whose month of birth, death, or migration was missing.

Middle-upper arm circumference. A total of 49,056 MUAC measurements were available (from the HDSS surveys) for 25,480 children younger than 5 years of age surveyed during the period of January 2009 to October 2014. Of these, 20,340 measurements on 16,698 children were taken over the period January 2009 to December 2012 (coinciding with the period for which survival data were available). Values of MUAC greater than 5 standard deviations from the mean (outside the range of 67–218 mm) were deemed implausible and excluded from analysis (15–17).

Agricultural yield data. Data on the annual yield (kg/ha) of each of the 5 main food crops in the Kossi province (millet, sorghum, fonio, maize, and rice), collected as a part of the national annual agricultural survey, were obtained from the agricultural statistics service of Burkina Faso for the period of 1992–2014. From these data we computed an annual food crop productivity index (FCPI). The FCPI represents a weighted average of the yield (kg/ha) of each of the main food crops (millet, sorghum, maize, fonio, and rice) relative to the period annual mean yield for 1992–2012, expressed as a percentage of the period average. It was calculated as follows:

$$\text{FCPI for year } i = \sum_{\mathrm{i}} p_{ij} \times w_{ij},$$

where p_{ij} is the yield in year i for crop j relative (percentage) to its mean yield over the period of 1992–2012, and w_{ij} is the proportion of the total harvest across the 5 crop types in year i from crop j.

Rice yield data was missing for the year 1994. The FCPI value for this year was calculated assuming the rice harvest proportion in 1994 was 0 (a minor assumption given the period average rice harvest proportion of only 0.4%). Given similar food energy value across the examined crop types (18), kcal expression of the weighting factors for crop-specific yields comprising FCPI here was unnecessary (calculation using energy equivalents leads to occasional decimal-point changes only).

Demographic and confounder data. Individual sex, ethnicity, religion, ability to read, familial links, and residence were obtained from the HDSS records. In addition, village-level data on infrastructural characteristics of Nouna HDSS villages (presence of markets, health-care facilities, and drilled water wells and the quality of road connections) were obtained from the Centre de Recherche en Santé de Nouna.

The study was conducted following the ethical standards of the Declaration of Helsinki (19) and was approved by the London School of Hygiene and Tropical Medicine Observational Ethics Committee and the Comité Institutionnel d'Ethique du Centre de Recherche en Santé de Nouna. Informed consent was obtained by the Centre de Recherche en Santé de Nouna from all subjects at the time of health and demographic data collection.

Analyses

We carried out 3 separate analyses: 1) the association of survival (from birth to 5 years of age) with FCPI, using data for 1992–2012; 2) the association of survival (to 5 years of age) with MUAC, using data for 2009–2012; and 3) the association of MUAC with FCPI using data for 2009–2014 (Figure 1). The timeframe of each analysis was determined by data availability (Web Table 1, available at https://academic.oup.com/aje).

Child survival was examined by tabulation, Kaplan-Meier plots, and Cox proportional hazards models with shared frailty specified by village and with age as the analysis time. Observations of children lost to follow-up before reaching 5 years of age were censored at the date of last contact.

For analyses of survival in relation to FCPI, survival from birth (to age 5 years) was related to the FCPI for the last harvest preceding or at the time of the date of birth (adjusting for the mean FCPI the child experienced from birth to 5 years of age). Separate models were constructed with FCPI fitted: 1) as a continuous numerical score (reporting model results as the hazard ratio for a 90th- to 10th-centile decrease in FCPI) and 2) as a binary classifier above and below the period average FCPI value.

For survival in relation to MUAC, follow-up was from the date of MUAC measurement and again continued to the age of 5 years. MUAC was treated as a time-varying exposure (thus allowing the incorporation of data for multiple MUAC measurements per child, where available). Before being included

Table 1. Number of Children, Deaths, Person-Years, and Mortality Rate According to Individual Characteristics (*n* = 44,616 Children), Nouna Health and Demographic Surveillance System, Burkina Faso, 1992–2012

Factor	No. of Children	% of Children	Deaths	Person-Years at Risk[a]	Mortality Rate per 1,000 Person-Years
Age, years					
0	44,616	100	2,069	40,305	51.33
1	37,040	83	1,295	33,171	39.04
2	30,939	69	757	27,700	27.33
3	26,246	59	272	23,625	11.51
4	22,613	51	142	20,306	6.99
Sex					
Male	22,358	50	2,395	72,806	32.90
Female	22,258	50	2,140	72,301	29.60
Ethnicity					
Bwamu	11,385	28	1,072	37,409	28.66
Dafing	17,426	39	1,968	56,617	34.76
Mossi	7,938	18	683	26,179	26.09
Phole	4,322	7	517	13,656	37.86
Samo	2,676	6	221	8,664	25.51
Other	822	2	67	2,466	27.17
Unclassified	47	0.1	7	116	60.36
Religion					
Animist	2,395	5	330	8,121	40.63
Catholic	11,893	27	1,022	38,802	26.34
Muslim	28,195	63	3,007	91,166	32.98
Protestant	1,997	5	157	6,646	23.62
Other	78	0.2	4	229	17.48
Unclassified	58	0.1	15	143	105.19
Mother's ability to read					
Unable	28,245	63	2,952	99,465	29.68
With difficulty	1,555	4	115	5,252	21.90
Easily	1,531	3	89	4,830	18.43
Unclassified	13,285	30	1,379	35,560	38.78
Father's ability to read					
Unable	25,153	56	2,616	85,860	30.47
With difficulty	3,437	8	288	12,119	23.77
Easily	3,074	7	207	10,522	19.67
Unclassified	12,952	29	1,424	36,607	38.90
Season at birth					
September–November	12,052	27	1,355	39,645	34.18
December–February	10,432	23	1,092	34,173	31.96
March–May	11,008	25	1,022	35,815	28.54
June–August	11,124	25	1,066	35,475	30.05
Season of exit from follow-up					
September–November	7,517	17	1,389	27,360	50.77
December–February	7,356	17	1,102	27,103	40.66
March–May	8,689	20	935	32,978	28.35
June–August	21,054	47	1,109	57,667	19.23

[a] Person-years at risk are presented from birth to the end of the follow-up period.

in the Cox models, all MUAC values were "corrected" for season of measurement using a linear regression model. Separate models were constructed with MUAC measurements fitted: 1) as numerical scores (reporting results as the hazard ratio for a 90th- to 10th-centile decrease in MUAC) and 2) as a 3-value classifier (in mm: <115, 115–125, >125).

For both sets of survival analyses (FCPI and MUAC), results are shown with adjustment for various combinations of potential confounders (2, 11, 20, 21) determined a priori. These confounders were sex, season of birth, ethnicity, religion, mother's and father's ability to read, semirural (Nouna town) versus rural residence (villages), indicators of village infrastructural characteristics (presence of a market, health-care facility, and drilled water wells and quality of road connections), a linear term for time trend (year), and a binary indicator of the existence of an undernutrition treatment program. In the case of models of survival in relation to MUAC, we also adjusted for the scale (mm vs. cm) in which the MUAC measurement was recorded during data collection.

The association of MUAC with FCPI was examined using multilevel linear regression models constructed with nested random effects at the level of village and individual (to account for repeated MUAC measurements on the same individuals) and using similar combinations of confounders to those indicated above and as shown in the tables. Separate multilevel linear regression models were constructed for FCPI at 3 time points: FCPI in the year of MUAC measurement (adjusting for the mean FCPI experienced from birth to measurement), year of birth (adjusting for the mean FCPI experienced between 1 and 5 years of age), and the lifetime average FCPI exposure, up to 5 years of age.

Sensitivity analyses for the association of child survival with MUAC were performed excluding children <6 months of age and using MUAC cutoffs of 115 and 125 mm to detect severe and moderate acute undernutrition (22).

All statistical analyses were performed using Stata, version 14.1 (StataCorp LP, College Station, Texas).

RESULTS

Characteristics of the study subjects monitored over the period of analysis for survival, 1992–2012, are given in the Table 1 and Web Table 2. Among the 44,616 children, 4,535 deaths were recorded, representing an average mortality rate of 31.25 deaths per 1,000 person-years at risk.

Characteristics of the 16,698 subjects with MUAC measurements monitored over the period of analysis of 2009–2012 are presented in Web Table 3. Mean MUAC among these subjects was 142 mm (95% confidence interval (CI): 141, 142). Five percent had MUAC of <115 mm and 9% had MUAC of 115–125 mm. The earliest MUAC measurements were made in the first month of life, with 43% made in the first and 21% between the first and second year of life.

Crop data showed the highest average yield (kg/ha) for maize, followed by rice, sorghum, and millet (Figure 2; Web Table 4). Interannual variability in the FCPI was driven mainly by changes in the productivity of millet and sorghum, because on average millet and sorghum together constituted 89% of the total harvest of all the 5 food crops in the Kossi province (Web Table 4). Over the 23 years of the study, the FCPI varied from the minimum of 65% to the maximum of 120% of the period average, with a 10th–90th centile interval of 82%–119%.

Survival

Kaplan-Meier plots showed mortality risk to be highest in the first 2–3 years of life. Survival was lower among children born in years of below-average FCPI than among children born in years of above-average FCPI (Figure 3). Results of the Cox regression analyses showed that child survival was associated with FCPI in the year of birth (Table 2), with a decrease in yield from 90th- to 10th-centile corresponding to hazard ratio of 1.11 (95% CI: 1.02, 1.20) in the fully adjusted analyses.

Survival was also associated with MUAC measurements (Table 3; Figure 4). A decrease in MUAC from 90th to 10th centile was associated with a hazard ratio of 2.72 (95% CI: 2.15, 3.44) in the fully adjusted analysis. For children with MUAC of <115 mm, the hazard ratio was 2.73 (95% CI: 2.10, 3.55), and for those with MUAC of 115–125 mm it was 1.94 (95% CI: 1.53, 2.48), compared with children with MUAC of >125 mm. With the exclusion of children less than 6 months of age, the hazard ratio for children with MUAC of <115 mm, representing severe acute undernutrition, increased to 3.60 (95% CI: 2.30, 5.63) but did not change for children with MUAC of 115–125 mm (Web Table 5).

MUAC in relation to FCPI

Children's MUAC was also related to FCPI in the year of MUAC measurement and to lifetime average FCPI (Table 4), although not with the FCPI in the year of birth. In fully adjusted analyses, a decrease from 90th to 10th centile in FCPI in the year of measurement was associated with a decrease of 2.62 mm (95% CI: 2.08, 3.15) in MUAC, and the corresponding figure in relation to lifetime average FCPI was a decrease of 3.81 mm (95% CI: 2.89, 4.73).

DISCUSSION

This study provides new evidence, based on analysis of longitudinal data, of the relationship between child survival, nutrition, and annual variation in crop yields in a subsistence-farming population of Burkina Faso. The main findings were that child survival was associated with food crop yield in the year of birth and with short-term nutritional status, reflected by MUAC, and that MUAC measurements themselves were related to crop yields in the year of measurement and over the child's lifetime (though not with yields in the year of birth). Poor nutrition may thus be at least in part a mediator of the relationship between low crop yields and survival. It is noteworthy that we did not find clear evidence that MUAC was related to crop yield in the year of birth despite evidence for poorer survival when there is a low yield in the year of birth. This may reflect the relatively long interval between birth and first MUAC measurement for many children (MUAC tends to indicate the nutrition of recent months).

These findings are broadly consistent with previously published research. Such research includes a study that found a positive association of childhood survival with spatial variability of food crop yield (approximated by mean normalized

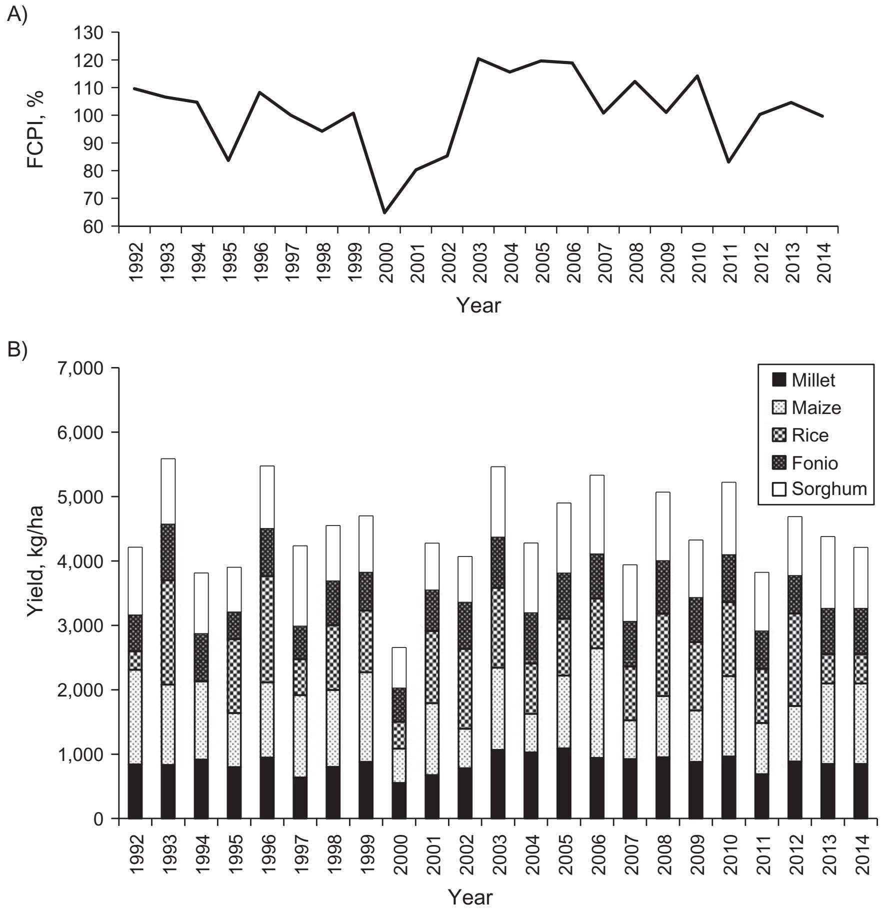

Figure 2. Time series of the food crop productivity index (FCPI) (A) and annual yield of each individual crop comprising the FCPI (B) in the Kossi Province, Burkina Faso, 1992–2014.

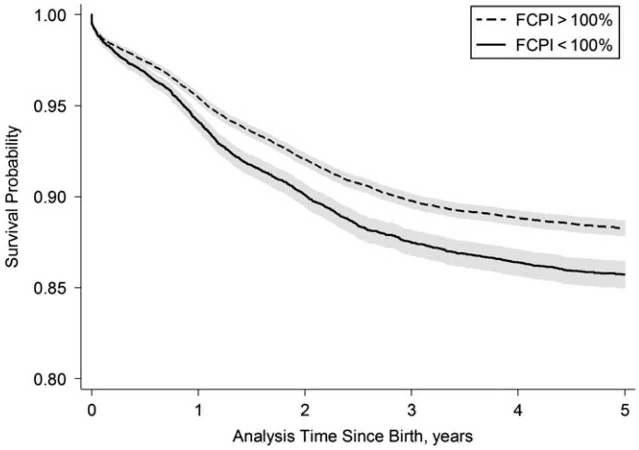

Figure 3. Kaplan-Meier plot of survival probability among children less than 5 years of age in relation to the food crop productivity index (FCPI) in the year of birth, Nouna Health and Demographic Surveillance System, Burkina Faso, 1992–2012. Follow-up period started on the date of birth; age is used as analysis time scale. Gray areas represent the 95% confidence interval, with darker areas representing their overlap.

difference vegetation index over the agricultural season) in the year of birth in Mali and Burkina Faso (11), seasonal differences in food availability in Gambia (23, 24), and annual rainfall (approximating drought conditions) in rural Burkina Faso (21) and India (25). Our findings are also consistent with studies reporting positive association of wasting (anthropometric measure used to determine the same type of undernutrition—acute undernutrition—as MUAC) with the same year normalized difference vegetation index in Nepal (8), normalized difference vegetation index in the year of birth in Mali (11), and drought at the time of birth in India (25). Our results also support prior findings of MUAC as a strong predictor of child mortality (22, 26).

If interpreted as reflecting causal associations, our results suggest that low food crop yields in the rural population of Burkina Faso limit food availability needed for children's growth and development, posing a risk for subsequent short- and medium-term health (survival). Of particular concern is the apparent association of low crop yield in the year of birth with childhood survival up to 5 years of age, suggesting a persisting adverse consequence of reduced food availability around the time of, or shortly after, birth.

Table 2. Association of Child Survival to 5 Years of Age With Food Crop Yield in the Year of Birth (*n* = 44,616 Children), Nouna Health and Demographic Surveillance System, Burkina Faso, 1992–2012

Model[a]	HR for All-Cause Mortality	95% CI
Model 1[b]		
Up to period mean FCPI[c]	1.00	Referent
Less than period mean FCPI	1.23	1.15, 1.31
Δ90p–10p FCPI[d]	1.15	1.07, 1.23
Model 2[e]		
Up to period mean FCPI[c]	1.00	Referent
Less than period mean FCPI	1.12	1.04, 1.20
Δ90p–10p FCPI[d]	1.12	1.03, 1.21
Model 3[f]		
Up to period mean FCPI[c]	1.00	Referent
Less than period mean FCPI	1.11	1.03, 1.18
Δ90p–10p FCPI[d]	1.11	1.02, 1.20
Model 4[g]		
Up to period mean FCPI[c]	1.00	Referent
Less than period mean FCPI	1.10	1.03, 1.18
Δ90p–10p FCPI[d]	1.11	1.02, 1.20

Abbreviations: Δ90p–10p, decrease from 90th to 10th centile; CI, confidence interval; FCPI, food crop productivity index; HR, hazard ratio.

[a] Cox proportional hazards models with age used as the analysis time and shared frailty specified by village. Therefore, random effects at the village level are adjusted for in all of the presented models.

[b] Model 1 had no fixed-effect adjustments.

[c] Baseline for the hazard ratio associated with below period-average FCPI.

[d] Obtained from modeling with FCPI as a continuous variable.

[e] Model 2 adjusted for the presence of an undernutrition treatment program, time trend, and mean FCPI exposure after the child's year of birth to the age of 5 years.

[f] Model 3, in addition to the adjustments of model 2, adjusted for season of birth, sex, ethnicity, religion, and mother's and father's ability to read.

[g] Model 4, in addition to the adjustments of model 3, adjusted for the presence of a market, health-care facility, and drilled wells and for road quality and semirural versus rural residence.

Table 3. Association of Child Survival to 5 Years of Age With Nutritional Status, as Measured by Middle-Upper Arm Circumference (*n* = 16,698 Children and 18,511 Measurements), Nouna Health and Demographic Surveillance System, Burkina Faso, 2009–2012

Model[a]	HR for All-Cause Mortality	95% CI
Model 1[b]		
MUAC >125 mm[c]	1.00	Referent
MUAC 115–125 mm	2.10	1.65, 2.67
MUAC <115 mm	3.05	2.36, 3.96
Δ90–10p MUAC[d]	3.04	2.42, 3.80
Model 2[e]		
MUAC >125 mm[c]	1.00	Referent
MUAC 115–125 mm	1.92	1.51, 2.44
MUAC <115 mm	2.71	2.09, 3.52
Δ90–10p MUAC[d]	2.66	2.10, 3.36
Model 3[f]		
MUAC >125 mm[c]	1.00	Referent
MUAC 115–125 mm	1.94	1.52, 2.46
MUAC <115 mm	2.73	2.10, 3.56
Δ90–10p MUAC[d]	2.70	2.13, 3.42
Model 4[g]		
MUAC >125 mm[c]	1.00	Referent
MUAC 115–125 mm	1.94	1.53, 2.48
MUAC <115 mm	2.73	2.10, 3.55
Δ90p–10p MUAC[d]	2.72	2.15, 3.44

Abbreviations: Δ90p–10p, decrease from 90th to 10th centile; CI, confidence interval; MUAC, middle-upper arm circumference; HR, hazard ratio.

[a] Cox proportional hazard models with age used as the analysis time and shared frailty specified by village. Therefore, random effects at the village level are adjusted for in all of the presented models.

[b] Model 1 had no fixed-effect adjustments.

[c] Baseline for the hazard ratio associated with MUAC of <115 mm and MUAC of 115–125 mm.

[d] Obtained from modeling with MUAC as a continuous variable.

[e] Model 2 adjusted for the presence of an undernutrition treatment program, time trend, and MUAC measurement scale.

[f] Model 3, in addition to the adjustments of model 2, adjusted for season of birth, sex, ethnicity, religion, and mother's and father's ability to read.

[g] Model 4, in addition to the adjustments of model 3, adjusted for the presence of a market, health-care facility, and drilled wells and for road quality and semirural versus rural residence.

What our analyses do not clearly distinguish is whether this is most likely to be a consequence of in utero exposures (poor nutrition of the mother leading up to birth) or of poor nutrition during the first year of life. Medical evidence demonstrates that undernutrition in utero and in early life (first 24 months) are each associated with long-term health consequences, such as impaired cardiac health (27) and kidney function (28), lower height, higher blood glucose concentrations, increased blood pressure, harmful lipid profiles, and higher chance of mental illness (29, 30). Studies of the health status of adult survivors who were exposed to historical famines in utero or early life in China, Russia, Finland, and Netherlands found poorer mental and physical health, manifested by impairments of the central nervous system, higher rates of coronary heart disease, metabolic dysfunction, and antisocial behavior (31–38). Furthermore, a study of the Bangladesh famine following monsoon flooding in 1974 found an increased mortality rate in the cohort of children born during the famine, as compared with the cohorts conceived during or after the famine (39). These studies suggest higher frailty of those exposed to food shortages in utero and in early life as well as higher risk of mortality in subsequent life. Such individuals might be even more vulnerable to later instances of low food availability (40).

Implications

The principal implication of our findings is that children in the subsistence-farming population of Nouna and potentially elsewhere may be vulnerable to reductions in food crop yield,

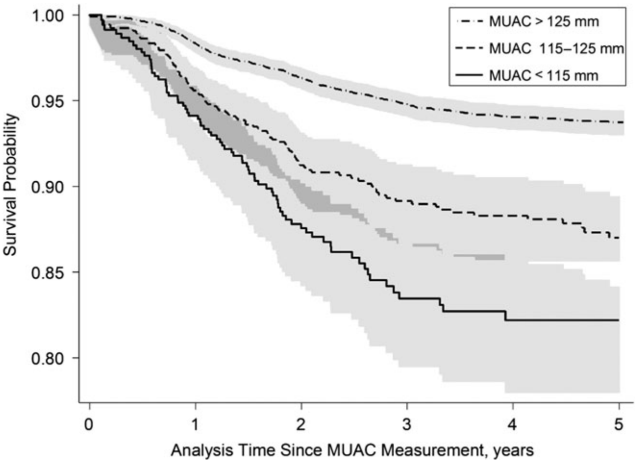

Figure 4. Kaplan-Meier plot of survival probability among children less than 5 years of age in relation to nutritional status, as measured by middle-upper arm circumference (MUAC), Nouna Health and Demographic Surveillance System, Burkina Faso, 2009–2012. Follow-up period started on the date of middle-upper arm circumference measurement; age is used as analysis time.

Table 4. Association of the Decrease in Children's Middle-Upper Arm Circumference With a Reduction in Food Crop Yield (*n* = 49,056 Children), Nouna Health and Demographic Surveillance System, Burkina Faso, 2009–2014

Model[a]	Decrease in MUAC, mm[b]	95% CI
Model 1[c]		
Lifetime average FCPI	6.52	5.80, 7.24
FCPI in the year of birth	3.20	2.75, 3.65
FCPI in the year of MUAC measurement	8.86	8.33, 9.39
Model 2[d]		
Lifetime average FCPI	2.46	1.58, 3.35
FCPI in the year of birth	−0.70	−1.27, −0.15
FCPI in the year of MUAC measurement	2.47	1.94, 3.01
Model 3[e]		
Lifetime average FCPI	3.81	2.89, 4.73
FCPI in the year of birth	−0.09	−0.66, 0.48
FCPI in the year of MUAC measurement	2.62	2.09, 3.16
Model 4[f]		
Lifetime average FCPI	3.81	2.89, 4.73
FCPI in the year of birth	−0.09	−0.66, 0.48
FCPI in the year of MUAC measurement	2.62	2.08, 3.15

Abbreviations: CI, confidence interval; FCPI, food crop productivity index; MUAC, middle-upper arm circumference.

[a] Random effects at the village and individual levels were specified in all of the models presented.

[b] With a 90th- to 10th-percentile decrease in FCPI.

[c] Model 1 had no fixed-effect adjustments.

[d] Model 2 adjusted for the presence of an undernutrition treatment program, time trend, MUAC measurement scale, and age and season at MUAC measurement as well as subsequent FCPI (used in models where FCPI in the year of birth was specified as the exposure), preceding FCPI (used in models where FCPI in the year of MUAC measurement was specified as the exposure), or neither of these adjustments (in models where lifetime average FCPI was used as the exposure).

[e] Model 3, in addition to the adjustments of model 2, adjusted for season of birth, sex, ethnicity, religion, and mother's and father's ability to read.

[f] Model 4, in addition to the adjustments of model 3, adjusted for the presence of a market, health-care facility, and drilled wells and for road quality and semirural versus rural residence.

which in areas of rain-fed agriculture is often related to unfavorable weather conditions over the growing season. This is of particular concern in the context of the projected increase in the frequency and severity of droughts and other drivers of increased crop-yield variability with further climate change in West Africa and other regions with a high prevalence of subsistence rain-fed agriculture (4, 41).

Adaptation responses should therefore take account of such potential impacts and incorporate careful nutritional monitoring in households with pregnant mothers, newborns, and young children, particularly in years with low crop yields. There may be value in considering measures that could protect against low crop yields and their consequences for health, such as early weather-warning systems, crop insurance systems, use of drought-resistant crops, improvement of irrigation, and improved health systems.

Limitations

First, we acknowledge that because the hazard ratios for survival in relation to FCPI are not large, there is the possibility that our results could be due to residual confounding. It is not clear what extrinsic time-varying factors associated with years of low FCPI could be important as confounders. Direct weather effects (i.e., on mortality as well as on crop yield) are a possible alternative explanation for very short-term associations, but not of the results for FCPI in the year of birth affecting later survival.

We used provincial food-crop yield records to derive a measure of relative food-crop yield variability (the FCPI) in our study population of Nouna HDSS, which covers approximately one-third of the province. Despite this approximation, we found strong associations of the relative yield measure with nutritional and mortality outcomes among children less than 5 years of age in this population. With no data on spatial yield variability across the province, we could not use year as an additional indicator variable to control for any potentially confounding temporal factors other than time trend (which we controlled for). Therefore, we explored the possibility of such factors through discussions with the local research center and context exploration. We identified the establishment of the undernutrition treatment program as the only potentially confounding temporal factor and controlled for it using a binary indicator variable. Further analysis based on more spatially refined resolution of annual crop-yield variability may provide even stronger associations than were identified here.

An even stronger association of survival with MUAC and MUAC with FCPI could be observed if the MUAC measurements in our data set were more equally distributed across seasons. In our data a relatively small number of MUAC measurements were made in the lean season (June–August), when household cereal stocks from the last harvest are running low and the proportion of children with low MUAC tends to be higher than in other seasons (42, 43).

As indicated above, our finding of no significant association of MUAC with FCPI in the year of birth (as opposed to FCPI in the year of MUAC measurement and lifetime average FCPI) could reflect the long interval between birth and first MUAC measurement. It may also reflect a bias that fewer children with low MUAC may survive to have a MUAC measurement in a low-FCPI year compared with a high-FCPI year. This bias cannot be directly quantified from our data but among those who had MUAC measurements in the first year of life, the mean MUAC was 126 mm (95% CI: 123, 129) among those who died before 12 months and 135 mm (95% CI: 134, 136) among those who survived to 12 months, with mortality rates of 30 versus 27 deaths per 1,000 children among those born in years with below- and above-average FCPI, respectively.

The analyzed data series were sufficient to examine each association of interest separately. The data series did not have a sufficient temporal overlap to permit formal mediation analysis and establish the extent to which the association of low crop yields with child survival was mediated by low MUAC as opposed to other processes.

Conclusion

The survival of children less than 5 years of age in the Nouna HDSS population was related to the food crop yield in their year of birth and to their nutritional status, as measured by MUAC. Children's MUAC was also associated with the relative yield of the preceding harvest and average yield over children's lifetime.

Our results suggest that child nutrition and survival in this, and possibly similar, subsistence-farming populations are vulnerable to interannual variation in food crop yield. This observation may become more significant with the increased variability in crop yields predicted under climate change. Methods of protecting against low crop yields, integrated with household nutritional monitoring, could help to reduce such adverse impacts.

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