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Title: Child survival and annual crop yield reductions in rural Burkina Faso: critical windows of vulnerability around early life development

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Abbreviations: AIC — Akaike Information Criterion, CI — Confidence Interval, FCPI — Food Crop Productivity Index, HDSS — Health and Demographic Surveillance System, HR — Hazard Ratio, NDVI — Normalized Difference Vegetation Index

Abstract

Populations reliant on subsistence farming are particularly vulnerable to climatic effects on crop yields. However, empirical evidence on the role of the timing of exposure to crop yield deficits around early life development is limited. We examined child survival in relation to annual crop yield reductions at different stages around early life development in a subsistence farming population in Burkina Faso. Using shared frailty Cox proportional hazards models adjusted for confounders, we analysed 57,288 children <5 years of age followed by the Nouna Health and Demographic Surveillance System, 1992–2016, in relation to provincial food crop yield levels experienced in the following non-overlapping windows: 12 months before conception, in utero, birth–6 months, 6 months–2 years, 2–5 years of age; and their aggregates: birth–2 years, first 1,000 days since conception, birth–5 years. Of the non-overlapping windows, point estimates were largest for child survival related to yields for the time window of 6 months–2 years: adjusted mortality hazard ratio 1.10 (95% confidence interval 1.03 to 1.19) for a 90th to 10th centile yield reduction. These findings suggest that child survival in this setting is particularly vulnerable to cereal crop yield reductions during the period of non-exclusive breastfeeding.

Children in subsistence farming populations of Sub-Saharan Africa are often exposed to food insecurity and may experience heightened risk of undernutrition and illness when crop yields are low (1). Climate change may aggravate these risks as changing temperature and rainfall patterns lead to greater fluctuations and less predictable food supply, particularly for households reliant on rainfed agriculture (2,3).

Adequate food intake in early life is essential for children's cognitive and physical development and lifelong health. The first 1,000 days from conception to 2 years of age are particularly critical due to high nutritional requirements for rapid growth and neurodevelopment (4–7). Inadequate energy and nutrient intake in this period is likely to result in stunting, lifelong deficit in brain function, and increased likelihood of subsequent cardiovascular, endocrine, and metabolic diseases, including obesity and impaired kidney function, as well as mental illness (4,7,8). Similarly, the mother's food intake before conception can influence child's risk of preterm birth, immune system and brain development (9,10). The impacts of food intake restriction before conception and in early life are not always reflected by changes in children's anthropometrics, as those can operate independently through early life nutritional programming of the immune system at epigenetic level (11–13).

Establishing the timeframes of greatest vulnerability to variations in crop yields can help identify opportunities for improving nutritional practices and programmes. Yet, evidence on effects of exposures to crop yield reductions (and such proxies as weather patterns during the growing season) at different stages of early life in vulnerable subsistence farming populations is scarce and inconsistent (1,14). A limited number of studies compared associations of child growth with exposures to the Normalized Difference Vegetation Index (NDVI) and rainfall shocks in the crop growing season one year before birth *vs* the first year of child's life (15,16), and some also with exposures in the second year of life (17,18). Their results were mixed, with varying evidence for associations during different windows of exposure in different settings. A more systematic examination is needed. As annual crop yield deficits are projected to worsen for West Africa under climate change (19), evidence is especially important to inform health- and nutrition-sensitive adaptation efforts to protect children.

Our earlier work in Burkina Faso showed that child survival to 5 years of age was associated with crop yield levels in their year of birth without distinguishing the effect of in utero exposures from those in the first year of life (20). We now examine child survival in relation to exposure to crop yield fluctuations at five periods in early child development: (i) exposures experienced by mothers before conception, (ii) exposures experienced in utero, (iii) in the first 6 months from birth, (iv) from 6 months to 2 years of age, (v) from 2 to 5 years of age, and their aggregates: lifetime average exposure, exposure over the 1,000 days since conception, and 0 to 2 years of age. We use the latest version of the longitudinal dataset of 24 years of follow up from Nouna Health and Demographic Surveillance System (HDSS). It is longer than the dataset used in our earlier work, enhancing the statistical power of the analyses (20).

Methods

Study population

Our study population is located in the Kossi province of Burkina Faso, which has been surveyed as an open dynamic continuous cohort as a part of the Nouna HDSS by the Centre de Recherche en Santé de Nouna (21). The population under surveillance has grown from 26,626 in 1992 to currently 150,000 through natural population growth and incorporation of additional villages(21). It relies almost entirely on rainfed subsistence agriculture with one agricultural season per annum, harvested around September.

Our data were obtained as follows.

(1) Outcome: child mortality/survival data

We acquired the latest available Nouna HDSS data covering 57,288 children under 5 years of age followed–up over 1994–2016, and including vital and migration events recorded through surveys that took place every three months until 2006 and every four months thereafter. Additionally, a control census was undertaken every five years. Individuals born before 1994, outside of the Nouna HDSS area, and individuals with missing records of their month of birth, death or migration were excluded. Data for the years 1992–1993 were not used for analyses due to concerns over data incompleteness, whilst the surveillance system was under development.

(2) *Exposure: agricultural yield data*

We obtained data on crop yields (kg/ha) in Kossi province, 1994–2016, from the national Annual Agricultural Survey of Burkina Faso (source: the Agricultural Statistics Service of Burkina Faso) (22) and calculated the Food Crop Productivity Index (FCPI) using previously published methods (20). The FCPI represents a weighted average of the yield of the five main food crops in the Kossi province (millet, sorghum, maize, fonio, and rice) relative to their annual mean yield over the period of 1994–2016, expressed as a percentage of the period average. Each crop type was weighted by the proportion of harvest that it contributed to the total harvest across the five crop types each year in the province.

(3) *Covariates: socio-demographic data*

HDSS data included individual demographic and socio-economic characteristics (sex, ethnicity, religion, ability to read, familial links, rural *vs* semi-rural residence), and household characteristics (presence of any members in occupations outside agriculture and a wealth index developed by Schoeps *et al* (2014) coded to quartiles). The wealth index represents household housing conditions (e.g. dwelling type, type of roof and walls, water source in the dry and rainy season, type of toilet and sanitation, source of lighting, energy source for cooking) and asset ownership (e.g. means of transport, agricultural assets, household items, such as radio, television, refrigerator, modern stove.) based on the data for 2009 (23). As the wealth index data were only available for 2009, we assigned the index value from 2009 to all years through which the household could be traced in our dataset over the analyses period from 1994–2016. We re-classified any missing data on individual and socio-economic characteristics into a separate category 'unclassified'. We also acquired data on infrastructural characteristics of Nouna HDSS villages from a geographical information system database of the Centre de Recherche en Santé de Nouna (presence of drilled water wells, markets, health care facilities, and the quality of road connection), from which we used principal component analysis to construct a village infrastructural development index (quartiles).

Analyses

To examine child survival in relation to exposure to crop yield variations at different stages of child development, we calculated exposure indices for the following periods (Figure 1):

(1) 12 months before conception, a window representing the mother's food intake that can affect child's development and health (9,10)
(2) first 1,000 days from conception (approximated as 270 days before and 730 days after birth), which we further separated into two sub-periods:
    a. in utero (approximated as 270 days before birth), and
    b. over the first two years since birth, further segmented into the sub-periods corresponding to different breastfeeding regimen recommendations by the World Health Organisation (24):
        i. 0–6 months – period of exclusive breastfeeding, and
        ii. 6 months–2 years – period of non-exclusive breastfeeding
(3) over 2–5 years
(4) from birth to 5 years

These exposure indices were calculated using data on each child's date of birth and exit from surveillance in relation to the timing of each agricultural harvest, assumed to start on 1st September. The index for each time window was calculated as a weighted average of the FCPI levels in the agricultural years that the period falls as the child ages, i.e., from the start of the window until death or exit from observation or end of the window, weighted by the proportion of time falling in each agricultural year. For example, if a child dies at the age of one year, his lifetime average exposure reflects the FCPI levels experienced in this one year of life; if a child dies at the age of three years, his lifetime average exposure represents the weighted average of FCPI levels experienced throughout the first three years of life. For comparability with our earlier work (20), we replicated the survival analyses in relation to the FCPI exposure in the agricultural year of birth, using the updated dataset. The year of birth exposure only considers the FCPI of the harvest year when the child was born disregarding the exposure to other FCPI levels in earlier and later agricultural years.

We examined associations of each exposure index with survival using tabulations, Kaplan Meier plots and Cox proportional hazards models with shared frailty specified by village and age used as the analysis time. First, a separate model was fitted for each exposure index separately. We then fitted models that simultaneously included indicators for more than one exposure window. Child observations that were lost to the follow up before reaching 5 years of age were censored on the date of exit from the surveillance. Models with the exposure of FCPI over 2–5 years of age were only based on observations of children who survived and were present at the HDSS at the age of 2 years.

For Kaplan Meier plots, each exposure index was transformed into a binary indicator above *vs* below the period average FCPI. For the Cox models, we used continuous exposure indices. The survival hazard ratios are reported in relation to the change in exposure from its 90^{th} to the 10^{th} centile.

All Cox models were adjusted for different combinations of potential confounders, which we determined a priori (1,16,25,26): (1) random effects at the village, with subsequent addition of adjustments for, (2) the establishment of a local undernutrition treatment programme (indicator of a step change in 2007) and a linear time trend (i.e., year fitted as a linear term to control for any long-term, continuous changes in child mortality and crop yields), and (3) all time-invariant socio-demographic characteristics of children, their households and villages: season of birth, sex, ethnicity, religion, mother's and father's ability to read, household's wealth index, presence of any members in the household involved in a non-agricultural occupation, level of village infrastructural development, semi-rural *vs* rural residence.

To examine if the expansion of the Nouna HDSS population by adding new villages in the years 2000 and 2004 could have biased our analyses, we performed sensitivity analyses by restricting the dataset to only those villages that were part of the HDSS since its inception.

We stratified the analyses of child survival in relation to one of the FCPI exposure indices by wealth index categories to explore if and how the association varies with household wealth.

Statistical analyses were performed using Stata 16.1 (27).

The study was conducted following the ethical standards of the Declaration of Helsinki (28) and was approved by the Ethics Committee of the Medical Faculty of Heidelberg University 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.

Results

The characteristics of the study population are presented in Table 1. There were 5,331 deaths with an average mortality rate of 26.22 deaths per 1,000 person-years.

Across all the exposure windows, FCPI values ranged from 49% to 139% of the period average weighted provincial yield. Table 2 gives the statistics by each exposure window. Most of these indicators are largely uncorrelated (Web Table 1). The variation in crop-specific yield and FCPI values across the study years is illustrated in Web Figure 1.

The unadjusted Kaplan Meier plots suggest poorer survival for children exposed to below period average FCPI in all time windows except for exposure after the second birthday (Figure 2). The difference in survival rates in relation to the FCPI appears to be the greatest for exposure of three overlapping time windows: the lifetime, the first 1,000 days from conception and the first 2 years since birth.

Results of Cox models with one exposure indicator fitted per model largely accord with the Kaplan Meier plots (Table 3), with relatively large (and statistically significant) point estimates for the first 1000 days, lifetime and 6 months to 2 year time windows, and lower (and statistically non-significant) results for pre-conceptional, gestational, 0–6 months, 2–5 years windows. Sensitivity analyses based on the subset of villages that were part of the HDSS since its inception show similar results (Web Table 2).

Cox models that simultaneously included indices for more than one non-overlapping exposure window showed comparatively large HRs for exposure in the window from 6 months to 2 years of age (Table 4 and Web Table 3). For example, the HR for 6 months–2 years was 1.15 (95% CI 1.04, 1.26) for a 90th to 10th centile yield reduction, when the model also included indices of the pre-conceptional, gestational, and first 6 months from birth windows. Evidence for the associations of child survival with pre-conceptional and gestational exposures was generally weak – HRs for the same level of crop yield reduction were 1.06 (95% CI 0.97, 1.15) and 1.04 (95% CI 0.93, 1.16), respectively. We found no evidence for the association with the exposure in the first 6 months from birth.

When the analysis was restricted to children surviving to 2 years, to enable the adjustment for exposures experienced from 2 to 5 years of age, there was no association detected for any of these exposure windows. However, the power to detect this association was limited by the smaller number of child observations eligible for these analyses (42,624 *vs* 57,288 children in other models).

The stratified analyses by wealth suggested a higher point estimate for the HR of child survival with the FCPI exposure in the window of 6 months to 2 years of age in the poorest quartile of households (Table 5). However, the evidence for these associations was weak due to the small number of observations per stratum.

Discussion

This study contributes new empirical evidence on the under-studied question of the timing of children's vulnerability to early life exposures to inter-annual crop yield reduction in a subsistence farming population in Sub Saharan Africa. It is the first study providing a detailed analysis of children's vulnerability to crop yield reductions segmented into the key stages around early life.

Although it is difficult to provide precise interpretation of the relative importance of different time windows, the evidence appears strongest for low FCPI being important in the period from 6 months to 2 years (Figure 3). The evidence was generally weaker for pre-conception and gestational exposures, for 0-6 months and for the period after 2 years.

In our study subjects the leading immediate causes of death in the age group of 6 months to two years are malaria (60%), diarrhoea and other gastrointestinal infections (11%), respiratory infections (8%), and meningitis (3%). Undernutrition is under-reported as a cause of death, as it underlies other causes and is rarely noted by physicians among the causes of death (29). It is estimated that globally undernutrition underlies 45% of deaths in children under 5 years of age (30). In Burkina Faso, cereal crops are essential for preparing porridges that are commonly introduced into children's diets as complementary food at the age of 6 months alongside breastfeeding and continued till 2 years of age (31). Vulnerability to cereal crop yield reductions in the window from 6 months to 2 years of age could be explained by the dependence of nutrition in this age group on cereal crop products, possibly further amplified by often late introduction of complementary feeding in this setting (31). Reduced crop yield may lead to sub-optimal food intake and limited means to access health care, thus, making children in this age group more vulnerable to the immediate causes of death in this age group. Our findings of weaker evidence in relation to cereal crop yield reductions in utero and in the first 6 months from birth could be related to physiological mechanisms that protect the nutritional needs of the foetus, e.g. placental phenotype alteration in circumstances of maternal nutrient restriction in an effort to maintain normal foetal growth, and breastfeeding (32). Similarly, the protective effect of immunisation and conditionality of survival to 2 years of age ("survival of the fittest") could to some degree explain our finding of no evidence for an association with exposures between 2 and 5 years of age.

We are aware of only one prior study that examined child mortality in relation to *both* pre-natal and early post-natal exposure to annual crop yield variation (16). It partly supports our findings with observed associations of child mortality with NDVI in the first year of life in dry settings (Burkina Faso in 2003, Mali in 2001) but not others (Benin in 2001, Guinea in 2005, Mali in 2006) (16), but whereas we found weak evidence for pre-natal exposure, the smaller (less powerful) and cross-sectional Johnson and Brown study found no association (16). Further studies examined crop yield variation proxies in the pre- and early post-natal period only in relation to child stunting. Stunting can be experienced as a result of restricted food intake in early life and periconceptional period and is strongly associated with the subsequent risk of mortality (8,14,23). It may, therefore, in part mediate the association of child mortality with early life exposures to yield fluctuations. The results of these studies are not entirely consistent. The majority suggested evidence for associations with both pre- and post-natal (first to second year since birth) exposures to yield reductions and their proxy indicators, NDVI and rainfall during crop growth (15,17,18). Only one study found no evidence of association of stunting and pre-natal exposures to NDVI and mixed evidence in relation to exposure over 0–2 years of age (16).

The differences in findings across studies could be due to differences in social, economic, and political circumstances which influence access to food, food prices, and level of support and health care, as well as the extent of the observed yield/NDVI variation (16). Mechanisms may also differ across settings and by timing, for example, impact through decreased household food availability *vs* income and resource availability for health care needs *vs* weather related changes in vector-borne disease risk. Adequate micronutrient intake may be more important in the perinatal period and in utero, while protein-energy intake in the post-natal stages (7,8). Furthermore, NDVI does not fully capture crop yield variations, as it only detects the intensity of the vegetation cover but not the extent of grain formation, which can be affected by rainfall shocks at specific stages of crop growth without a visible impact on vegetative parts of the plant (33). More advanced methods of micro-yield monitoring using satellite imagery at different stages of crop growth offer far more accurate yield assessment (34). Equally, the effect of spatial variability in NDVI, as for example, captured by Johnson and Brown (16) may not be directly comparable with the effects of inter-annual variability in crop yield examined in our analyses.

Our findings of vulnerability in our study population and potentially in similar populations, to early life reductions in crop yields are of particular concern given the projections of further crop yield reductions and increased frequency and intensity of droughts in West Africa with future climate change (35). In earlier work, we established that 72% of inter-annual variation in crop yields is related to adverse weather patterns during the crop growing season (36). Based on our previously identified association of child survival with crop yield variations in the year of birth (20), we estimated that changes in the frequency of adverse weather patterns and their impact on crop yield appreciably increased child mortality in Nouna even under the aspirational target of maintaining global average temperature increase below 1.5^{o}C (36). Our current analyses of separate windows of child vulnerability to crop yield reductions showed an even higher mortality hazard ratio in relation to crop yield reductions in the window of 6 months to 2 years (20) which may have bearing on the impact of climate change onchild mortality. There is a need and opportunity to design more effective adaptation strategies to crop yield reductions and the processes that lead to child vulnerability in the 6 months–2 years window, e.g., strengthening the resilience of healthy complementary feeding practices in times of food insecurity. If further evidence from other settings supports our findings, regular monitoring efforts would need to be prioritised in this section of population in Burkina Faso and the wider region to protect against potential increases in the effects of low crop productivity on child health. More resilient agricultural systems and improved management practices are also essential.

As in any observational study, we can't exclude residual confounding. However, our analyses were adjusted for all known time-varying confounders, including a linear time trend and the introduction of undernutrition treatment programme (20). In contrast to our earlier work (20), the current analyses explored and incorporated further adjustments for socio-economic differences (household wealth, involvement in non-agricultural employment, village infrastructural development). As the household wealth data were available only from the year 2009, we had to assume the wealth values from this year for the entire study period. Yet, the effect of wealth on child mortality was not the main focus of our analyses. As the study design compares the entire population against itself in one year against another and, as our results demonstrate, the effect of adjusting our analyses for individual and household characteristics is minimal. Therefore, the time-invariant nature of the wealth index is unlikely to have notable bearing on our results. Our identified associations remained statistically significant regardless of these adjustments. Our analyses did not allow distinguishing the extent to which the association of food crop yield variations with child mortality was mediated by own cereal crop consumption *vs* cereal crop purchases or sales, which remains an area for future research. However, studies in the area suggest that about 90% of what households eat has been grown and harvested in their own fields (37). Finally, the extent to which we were able to compare the importance of specific time windows of children's exposure to crop yield variations was limited by the nature of the local agricultural calendar with only one crop cultivation season per year. As a result, the exposure indices often overlapped by at least one agricultural year, and hence, one common yield value. For example, a child born on 20 December 2018, in utero would be exposed to a weighted average of yield values of the harvests of September 2017 and 2018 and in the first two years of life to the weighted average of the yield values of the harvests of September 2018, 2019, and 2020. Hence, the two exposure values would to some extent be inter-dependent as both incorporate the yield value of the same harvest of September 2018. Similar analyses in settings with multiple crop seasons per calendar year would provide greater variability across the exposure indices reflecting different time periods of early life development, and may therefore, provide clearer comparison of the differential effects of exposures in one window *vs* another. Future research could attempt developing and using the estimates of crop yield variability at a higher spatial resolution than the area of the province to capture spatio-temporal variability in crop yields across the study population, capturing such localised disruptions to crop production as flooding. Other topics to explore in future work include analyses of how health care access mediates the association of annual crop yield variation with child mortality.

Conclusion

In the Nouna area of Burkina Faso child health appears to be particularly vulnerable to cereal crop yield reductions in the period from 6 months to 2 years of age – the period of complementary feeding, often using cereal porridges alongside breastfeeding. This finding is particularly important in the context of the projected reductions and increased unpredictability of crop yields due to the increased weather variability with climate change in West Africa. It suggests opportunities for improving the effectiveness and efficiency of climate change adaptation policies for nutrition and health, s as well as for other nutritional interventions and support in our study area and potentially similar areas.

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Table 1. Descriptive statistics of children in our analyses data from Nouna HDSS, Burkina Faso, 1994–2016

Factors	No. of children	% of children	Deaths	P-y at risk	Mortality rates per 1,000 p-y
Age[a]					
0 -	57,288	100	2,440	6,462	377.58
1 -	48,828	85	1,527	12,705	120.19
2 -	41,460	72	902	16,593	54.36
3 -	35,240	62	313	17,004	18.41
4 -	30,498	53	149	150,529	0.99
Sex					
Boys	28,793	50	2,799	101,963	27.45
Girls	28,495	50	2,532	101,330	24.99
Ethnicity					
Bwamu	14,501	25	1,221	52,126	23.42
Dafing	22,426	39	2,345	79,663	29.44
Mossi	10,014	17	784	35,820	21.89
Peul/Fulani	5,760	10	643	19,686	32.66
Samo	3,435	6	258	12,254	21.05
Other	1,081	2	74	3,519	21.03
Unclassified	71	0	6	224	26.81
Religion					
Animist	2,700	5	335	9,872	33.93
Catholic	15,187	27	1,191	54,421	21.88
Muslim	36,696	64	3,624	129,186	28.05
Protestant	2,552	4	168	9,294	18.08
Other	107	0	5	382	13.08
Unclassified	46	0	8	137	58.59
Mother's ability to read					
Unable	29,828	52	3,264	127,820	25.54
With difficulty	1,680	3	128	7,280	17.58
Easily	1,746	3	105	7,238	14.51
Unclassified	24,034	42	1,834	60,955	30.09
Father's ability to read					
Unable	26,828	47	2,933	114,066	25.71
With difficulty	3,667	6	321	15,858	20.24
Easily	3,331	6	231	14,231	16.23
Unclassified	23,462	41	1,846	59,137	31.22
Season at birth					
Sep-Nov	15,624	27	1,576	55,662	28.31
Dec-Feb	13,287	23	1,289	47,348	27.22
Mar-May	14,257	25	1,222	50,608	24.15
Jun-Aug	14,120	25	1,244	49,675	25.04
At least one household member occupied outside agriculture[b]					
No	41,947	73	3,727	146,895	25.37
Yes	4,110	7	416	15,289	27.21
Unclassified	11,231	20	1,188	41,109	28.90
Wealth					
Level 1 (poorest)	10,129	18	1,133	37,846	29.94
Level 2	10,772	19	1,143	39,613	28.85

Level 3	11,674	20	1,082	43,039	25.14
Level 4 (wealthiest)	9,264	16	775	34,101	22.73
Unclassified	15,449	27	1,198	48,694	24.60
Village infrastructure level					
Level 1 (lowest)	18,369	32	2,004	64,514	31.06
Level 2	18,700	33	1,761	66,332	26.55
Level 3	7,041	12	793	25,974	30.53
Level 4 (highest)	13,178	23	773	46,473	16.63

Abbreviations: p-y, person-years.

[a]The number of children in each of the subsequent age groups is a subset of the survivors from the preceding age group.

[b]In addition to agricultural work of other members

Table 2. Descriptive statistics of the exposure measure by timing of exposure in Nouna HDSS area, Burkina Faso, 1993–2016

Timing of FCPI exposure	Median	Min, Max	10, 90th percentile	90th-10th percentile range
Before conception	100	52, 138	78, 119	-41
First 1,000 days	105	49, 139	80, 116	-36
Gestational	101	49, 139	78, 122	-44
0–2 years	103	61, 134	80,118	-38
0–6 months	102	61, 134	80, 120	-40
6 months–2 years	104	61, 134	81, 115	-34
2–5 years	105	61, 134	80, 119	-39
Lifetime average	105	61, 134	81, 115	-34
Year of birth	100	61, 134	78, 120	-42

Abbreviations: 10, 90p: the value of the 10th and 90th centile of each exposure indicator; Δ90-10p: difference between the values of the 10th and 90th centile of each exposure indicator

Table 3. Results of Cox regression analysis: child survival to 5 years of age in relation to individual food crop yield exposure indices in Nouna HDSS, Burkina Faso, 1994–2016

FCPI exposure	No. of children	Model 1[a]		Model 2[b]		Model 3[c]		
		HR	95% CI	HR	95% CI	HR	95% CI	AIC[d]
Before conception	57,288	1.37	1.28, 1.47	1.08	1.00, 1.17	1.06	0.98, 1.14	113728.7
First 1,000 days	57,288	1.44	1.35, 1.55	1.13	1.04, 1.23	1.12	1.03, 1.22	113723.3
Gestational	57,288	1.28	1.20, 1.37	1.06	0.99, 1.14	1.05	0.98, 1.14	113728.6
0–2 years	57,288	1.41	1.31, 1.51	1.12	1.03, 1.22	1.12	1.03, 1.22	113868.9
0–6 months	57,288	1.28	1.19, 1.37	1.05	0.97, 1.13	1.04	0.97, 1.12	113729.4
6 months–2 years	57,288	1.34	1.26, 1.42	1.10	1.02, 1.18	1.10	1.03, 1.19	113723.7
2–5 years[e]	42,624[a]	1.21	1.06, 1.39	0.87	0.75, 1.02	0.88	0.75, 1.03	29029.9
Lifetime average	57,288	1.34	1.26, 1.42	1.10	1.02, 1.18	1.10	1.02, 1.18	113723.9
Year of birth	57,288	1.27	1.20, 1.36	1.08	1.01, 1.16	1.08	1.01, 1.16	113726.2

Abbreviations: AIC, Akaike information criterion; CI, confidence interval; HR, hazard ratio; FCPI, food crop productivity index.

[a] Model 1 with random effects (shared frailty by village), unadjusted for other variables.

[b] Model 2 additionally to Model 1 adjustments, adjusted for the presence of undernutrition treatment programme (indicator of step change in 2007), time trend.

[c] Model 3 additionally to Model 2 adjustments, adjusted for season of birth, sex, ethnicity, religion, mother's and father's ability to read, household's wealth index, presence of any members in the household involved in a non-agricultural occupation, level of village infrastructural development, and semi-rural *vs* rural residence.

[d] AIC values are presented for the fully adjusted models (Model 3)

[e] To enable fitting the FCPI exposure over 2–5 years of age, the analyses dataset had to be restricted to the observations of these children who survived to and remained present in Nouna HDSS at 2 years of age.

Table 4. Results of Cox regression analysis: child survival to 5 years of age in relation to multiple simultaneously fitted exposure indices in Nouna HDSS, Burkina Faso, 1994–2016

FCPI exposure timings	No. of children	Model 1[a]		Model 2[b]		Model 3[c]	
		HR	95% CI	HR	95% CI	HR	95% CI
Models on full dataset[d]	57,288						
Before conception		1.31	1.22, 1.41	1.08	1.00, 1.18	1.06	0.97, 1.15
Gestational		1.05	0.94, 1.16	1.03	0.92, 1.14	1.04	0.93, 1.16
0–6 months		0.92	0.82, 1.04	0.93	0.82, 1.06	0.92	0.81, 1.04
6 months–2 years		1.34	1.23, 1.46	1.14	1.03, 1.25	1.15	1.04, 1.26
Models on the restricted dataset[e]	42,624						
Before conception		1.45	1.25, 1.67	1.16	0.98, 1.37	1.14	0.96, 1.34
Gestational		1.08	0.88, 1.31	0.99	0.81, 1.22	0.99	0.81, 1.22
0–6 months		0.97	0.80, 1.18	0.92	0.76, 1.13	0.92	0.75, 1.12
6 months–2 years		1.23	0.93, 1.63	0.88	0.65, 1.20	0.88	0.65, 1.20
2–5 years		1.05	0.83, 1.34	0.97	0.75, 1.24	0.97	0.75, 1.24

Abbreviations: CI, confidence interval; HR, Hazard ratio; FCPI, food crop productivity index.
[a] Model 1 with random effects (shared frailty by village), unadjusted for other variables.
[b] Model 2 additionally to Model 1 adjustments, adjusted for the presence of undernutrition treatment programme (indicator of step change in 2007), time trend.
[c] Model 3 additionally to Model 2 adjustments, adjusted for season of birth, sex, ethnicity, religion, mother's and father's ability to read, household's wealth index, presence of any members in the household involved in a non-agricultural occupation, level of village infrastructural development, and semi-rural *vs* rural residence.
[d] Models on full dataset, without adjustment for FCPI exposure over 2–5 years
[e] Models on the restricted dataset[e], with adjustment for FCPI exposure over 2–5 years. To enable the simultaneous adjustment for the FCPI exposure over 2–5 years of age, the analyses dataset had to be restricted to the observations of these children who survived to and remained present in Nouna HDSS at 2 years of age.

Table 5. Results of the stratified analyses by wealth: child survival to 5 years of age in relation to FCPI over 6 months – 2 years of age in Nouna HDSS, Burkina Faso, 1994–2016

Level of household wealth	No. of children	Model 1[a]		Model 2[b]		Model 3[c]	
		HR	95% CI	HR	95% CI	HR	95% CI
Level 1 (poorest)	7,950	1.40	1.21, 1.63	1.18	0.99, 1.41	1.17	0.98, 1.40
Level 2	8,448	1.21	1.04, 1.40	1.12	0.94, 1.33	1.11	0.93, 1.33
Level 3	8,012	1.24	1.06, 1.45	0.99	0.82, 1.20	0.97	0.80, 1.17
Level 4 (wealthiest)	3,469	1.22	0.99, 1.52	1.15	0.89, 1.49	1.15	0.89, 1.49
unclassified	11,091	1.35	1.17, 1.56	1.16	0.98, 1.38	1.17	0.99, 1.40

Abbreviations: CI, confidence interval; HR, hazard ratio; FCPI, food crop productivity index.
[a] Model 1 with random effects (shared frailty by village), unadjusted for other variables.
[b] Model 2 additionally to Model 1 adjustments, adjusted for the presence of undernutrition treatment programme (indicator of step change in 2007), time trend.
[c] Model 3 additionally to Model 2 adjustments, adjusted for season of birth, sex, ethnicity, religion, mother's and father's ability to read, household's wealth index, presence of any members in the household involved in a non-agricultural occupation, level of village infrastructural development, and semi-rural *vs* rural residence.

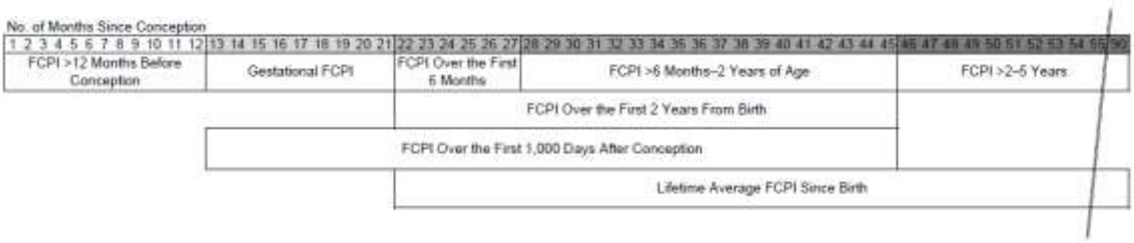
Fig 1. Exposure timings

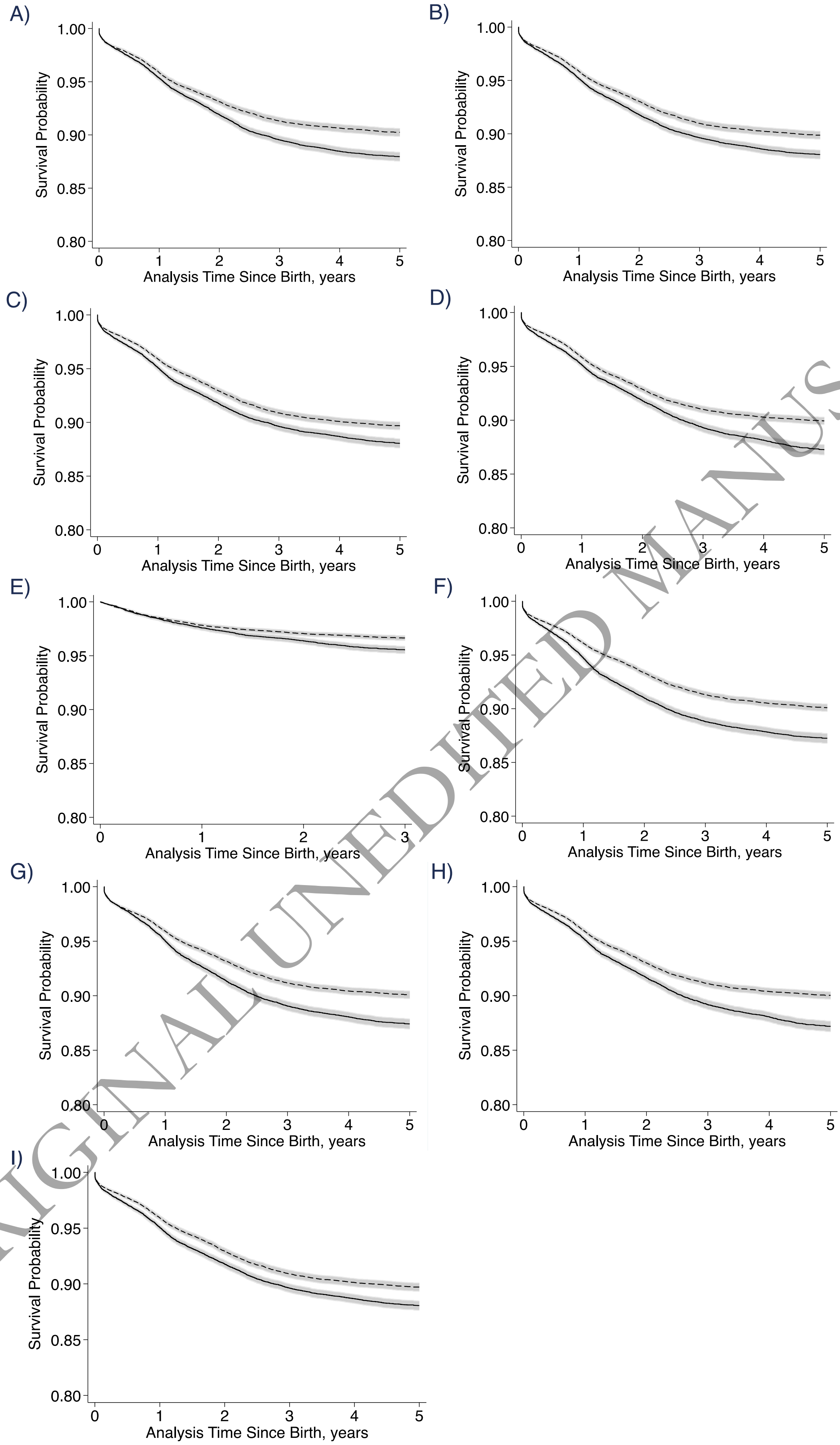
Abbreviations: FCPI – Food Crop Productivity Index.

Figure 2. Unadjusted Kaplan Meier estimates by timing of exposure in Nouna HDSS area, Burkina Faso, 1994–2016. A) FCPI exposure over 12 months before conception, B) Gestational FCPI exposure, C) FCPI exposure over the first six months from birth, D) FCPI exposure from six months to two years of birth, E) FCPI exposure from two to five years of age, F) FCPI exposure over the first two years from birth, G) FCPI exposure over the first 1,000 days from birth, H) Lifetime average FCPI exposure, I) FCPI in the first year of birth. Legend: solid line – survival probability in children exposed to FCPI<100%, dashed line – survival probability in children exposed to FCPI>100%. Abbreviations: FCPI – Food Crop Productivity Index.

Figure 3. Summary of findings on the associations of child survival with annual crop yield reductions during different windows of exposure. Colour coding: red – strong association, yellow – borderline/weak association, green – no significant association.

Abbreviations: FCPI – Food Crop Productivity Index.


No. of Months Since Conception
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54
FCPI >12 Months Before Conception
Gestational FCPI
FCPI Over the First 6 Months
FCPI >6 Months–2 Years of Age
FCPI >2–5 Years
FCPI Over the First 2 Years From Birth
FCPI Over the First 1,000 Days After Conception
Lifetime Average FCPI Since Birth


A)
Survival Probability
1.00
0.95
0.90
0.85
0.80
0
1
2
3
4
5
Analysis Time Since Birth, years
B)
Survival Probability
Analysis Time Since Birth, years
C)
Survival Probability
Analysis Time Since Birth, years
D)
Survival Probability
Analysis Time Since Birth, years
E)
Survival Probability
Analysis Time Since Birth, years
F)
Survival Probability
Analysis Time Since Birth, years
G)
Survival Probability
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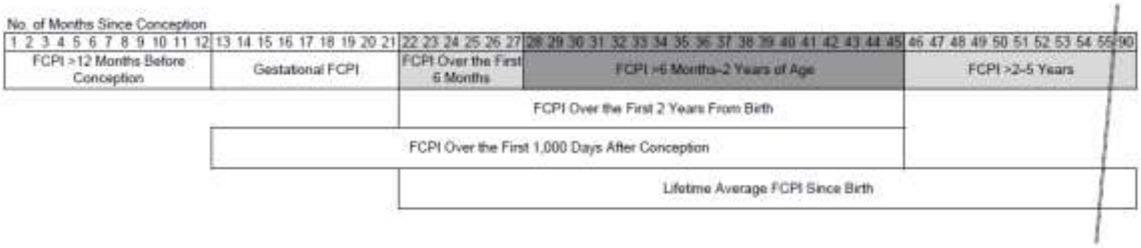
H)
Survival Probability
Analysis Time Since Birth, years
I)
Survival Probability
Analysis Time Since Birth, years


No. of Months Since Conception
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 90
FCPI >12 Months Before Conception
Gestational FCPI
FCPI Over the First 6 Months
FCPI >6 Months–2 Years of Age
FCPI >2–5 Years
FCPI Over the First 2 Years From Birth
FCPI Over the First 1,000 Days After Conception
Lifetime Average FCPI Since Birth