Crop Yields, Child Nutrition and Health in Rural Burkina Faso in the Context of Weather Variability: An Epidemiological Study

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To my mother

For all your love!

Declaration by the candidate

I, Kristine Belesova, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Signed:

[redacted]

6th February 2018

Abstract

Background: Undernutrition may become the most significant impact of climate change on child health, especially in subsistence farming populations, because of adverse effects of changes in weather patterns on crop yields and consequent undernutrition-related morbidity and mortality. However, empirical evidence is limited.

Aim: To examine crop yield variation as a risk factor for child undernutrition and mortality in the context of weather variability in a subsistence farming population of rural Burkina Faso.

Methods: Epidemiological analyses in the Nouna Health and Demographic Surveillance System of: (1) the association of child Middle-Upper Arm Circumference (MUAC) with crop harvest and annual yield variation, and (2) associations of child survival with annual crop yield variation and with MUAC. Analysis of observed weather–crop yield associations was used to predict future yields and child mortality attributable to annual yield reductions using daily weather data from global climate models that assume 1.5°C global warming by 2100.

Results: There was evidence that lower household crop harvests are associated with reduced MUAC, and annual yield reductions with both smaller MUAC and poorer child survival (hazard ratio for mortality of 1.11 (95% CI 1.02, 1.20) for a 90th–10th centile decrease in yield). Burden estimates suggest that low crop yields account for 7 child deaths per year in a population of 100,000 people of all ages under the current weather conditions, and a larger burden under trajectories consistent with 1.5°C global warming by 2100.

Conclusion: I found evidence of crop yield variation as a risk factor for child undernutrition and mortality in a subsistence farming population of rural Burkina Faso. The impact of such variation is likely to be exacerbated under climate change. This evidence strengthens the case for protection of child nutrition and health by addressing crop yield deficits in the context of weather and climate variability.

Acknowledgements

This thesis would not have been possible without the support of those who guided, advised, and encouraged me throughout the process. Foremost, I am eternally grateful to my supervisor Prof. Paul Wilkinson for his time, commitment, and expertise. His continuous guidance, support, and advice have been invaluable throughout these years. Thank you for helping me find 'more than one way to skin the cat'! I am also highly grateful to Prof. Rainer Sauerborn particularly for inspiration for this topic and for help in developing collaborations with the Centre de Recherche en Santé de Nouna and Potsdam Institute for Climate Impact Research.

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Preface

This thesis is written in the “Research Paper Style” format, following guidelines of the London School of Hygiene and Tropical Medicine. Therefore, all chapters of this thesis, except the first (*Introduction*) and the last (*Discussion*), are structured for publication in academic journals. The paper-based chapters contain a preamble, cover sheet, description of candidate’s contribution, a paper, any supplementary material pertaining to the paper (except in Chapters 2 and 6), and commentary with additional discussion points highlighting methodological questions and implications of each paper in relation to the thesis aim and objectives. Annex contains ethics approval letters and the extensive supplementary material of two papers from Chapters 2 and 6. The thesis is formatted uniformly including the last version of each paper as it was submitted to the journal (or as prepared for submission). References used in each paper are provided at the end of the paper, formatted following the journal requirements. References used in the remaining text of the thesis (Chapters 1, 3, 7 and commentaries of Chapters 2, 4–6) are provided as one list at the end of the thesis.

Candidate’s contribution

This thesis represents my own account of the investigation, where I identified the research gap, developed the thesis aim and objectives, the structure of the research programme, selected methods, and performed the analyses. My supervisor Prof. Paul Wilkinson provided input into the formulation of the aim and objectives as well as the methodological approach. The four research papers included in the chapters of the thesis presented findings of my research. I am the first author on each of these papers, having conceptualised and designed the corresponding studies and taken the lead on writing the manuscripts, coordinating co-author input and responding to their comments, corresponding with the journals, drafting responses to reviewers’ comments and editing all manuscript versions. Prof. Paul Wilkinson critically revised and co-authored all papers. Additional input was provided by other co-authors of each paper, as specified in the statements on multi-authored work included to precede each paper. I was the sole author of all the parts of the thesis that are not prepared for publication, reflecting my own interpretation and reflection on the context and findings of this thesis. Prof. Paul Wilkinson critically reviewed and commented on these parts of the thesis. I revised all drafts of the thesis text and prepared its final version.

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Abbreviations

AIC	Akaike Information Criterion
CI	Confidence Interval
CrI	Credibility Interval
CRSN	Centre de Recherche en Santé de Nouna
DHS	Demographic and Health Survey
E_f	Energy value of average daily household food cereal crop produce
E_{fc}	Energy value of average daily household food and cash crops combined
EVI	Enhanced Vegetation Index
FAO	Food and Agriculture Organization
FCFA	Franc de la Communauté Financière d'Afrique
FCPI	Food Crop Productivity Index
GAM	Global Acute Malnutrition
GCM	General Circulation Model
GDP	Gross Domestic Product
Hb	Haemoglobin
HDSS	Health and Demographic Surveillance Site
HIV	Human Immunodeficiency Virus
Ht/Age	Height-for-Age
Htc	Haematocrit
INDEPTH	International Network for the Demographic Evaluation of Populations and their Health
IPCC	Intergovernmental Panel on Climate Change

IPSL-CMSA-LR	Institute Pierre Simon Laplace Climate Model
IQR	Interquartile Range
ISI-MIP	Inter-Sectoral Impact Model Intercomparison Project
kcal/e/d	Kilocalories per adult equivalent per day
LMICs	Low- and Middle- Income Countries
LR	Likelihood Ratio
MDG	Millennium Development Goal
MIROC	Model for Interdisciplinary Research on Climate
MUAC	Middle-Upper Arm Circumference
NCHS	National Centre for Health Statistics
NDVI	Normalized Difference Vegetation Index
NGO	Non-Governmental Organisation
OECD	Organization for Economic Cooperation and Development
OR	Odds Ratio
PPP	Purchasing Power Parity
RESET	Regression Equation Specification Error Test
SD	Standard Deviation
SDG	Sustainable Development Goal
SES	Socio-Economic Status
SOFITEX	Societé Burkinabé des Fibres et Textiles
UNFCCC	United Nations Framework Convention on Climate Change
UNICEF	United Nations Children’s Fund
USD	U.S. Dollars
VSLY	Value of Statistical Life Year
WA-FCPI	Weather Attributable Food Crop Productivity Index

WFDEI	Water & Global Change Forcing Data Methodology Applied to European Centre for Medium-Range Weather Forecasts Re-Analysis Interim data
WHO	World Health Organisation
Wt/Age	Weight-for-Age
Wt/Ht	Weight-for-Height
WTP	Willingness to Pay

Key terminology

Acreage	area of land (ha) cultivated to produce crops.
Agricultural year	a period of 12 months starting with the start of the crop harvest (in the study area of this thesis assumed as the 1st September) and ending with the start of the following crop harvest.
Agricultural production	here used to refer collectively to crop cultivation process and its produce, e.g., characterised by the measures of harvest (kg) and yield (kg/ha).
Anthropometric measures	body measurements such as weight, height, and middle-upper arm circumference. Anthropometric measures (or their transformation into indices, e.g., relatively to age) are used to approximate an individual's growth or failure to grow and their nutritional status [1].
Annual crop yield variation	change in crop yield in one year compared to another year or to a statistical summary measure (e.g., mean) of yield level in a number of years.
Climate change	"change in the state of the climate that can be identified (e.g., using statistical tests) by changes in the mean and/or the variability of its properties and that exists for an extended period, typically decades or longer" [2, p78].
Climate change adaptation	"adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities" [3].
Climate change mitigation	"an anthropogenic intervention to reduce the anthropogenic forcing of the climate system; it includes strategies to reduce greenhouse gas sources

	and emissions and enhancing greenhouse gas sinks" [3].
Crop harvest	amount of a crop (kg) produced in one agricultural year.
Crop yield	a measure of the crop productivity, derived as a proportion of crop harvest per cultivated area of land (kg/ha).
Drought	here qualitatively defined as a phenomenon broadly characterized by reductions in water supply, and possibly in crop yield (further explained in Chapter 2).
Food crop productivity index	a summary measure of the annual yield of the key cereal food crops, expressed as the percentage of the period average yield (%) (details in Chapter 5).
Food energy	chemical energy derived from food; the energy is used by the body in metabolic processes and is measured in calories.
Food security	"a state when all people at all times have physical and economic access to sufficient safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life" [4, p1]. It is based on three pillars: food availability – sufficient quantity of food of adequate quality, food access – adequate resources to acquire appropriate foods, utilization – sufficient nutrient and energy intake, resulting from appropriate food preparation, diet, intra-household food distribution, feeding practices, good care, and stability – access to adequate food at all times [4,5].
General circulation models	numerical models representing physical processes in the atmosphere, ocean, cryosphere, and land surface to simulate the response of the global climate

	system to increasing greenhouse gas concentrations in the atmosphere [6].
Hazard ratio	the ratio of the chance of a negative health outcome at one level of exposure *vs* the chance of this outcome at another level of exposure.
Health and demographic surveillance system (HDSS)	a dynamic cohort that is defined as the total population in a specific geographic area and is followed by a research organization, recording dated vital events in this population [7].
Household	a socio-economic unit whose members are usually, but not necessarily, related by family ties; household members live together, share resources, and jointly meet their nutritional and other vital needs under the authority of a single person, referred to as the head of the household [8].
Middle-upper arm circumference (MUAC)	"the circumference of the left upper arm, measured at the mid-point between the tip of the shoulder and the tip of the elbow" [9]. This approximates an individual's nutritional status, which is sensitive to short-term changes in food intake. Below certain cut-off values it indicates a state of severe and moderate acute undernutrition.
Rainfed agriculture	crop cultivation relying on natural precipitation without irrigation.
Subsistence farming	"a form of agriculture where almost all production is consumed by the households, often characterized by low input use, generally provided by the farm" [10, p93].
Stunting	a state of suboptimal height for one's age. It is determined by the anthropometric index of height-for-age being two or more standard deviations below the internationally recognized median value in well-

	nourished individuals. It approximates the state of chronic undernutrition.
Survival probability	a statistical measure describing the chance of an individual's survival (here used as outcome measure in Cox proportional hazard regression models, Chapter 5).
Undernutrition	a state of deficiency of nutrients and energy in the human body, which leads to adverse effects on body form, function and clinical outcome [11]. Undernutrition is a sub-category of the term "malnutrition", which encompasses undernutrition (concerns the state of deficiency) and overnutrition (concerns the state of excess) [12]. Micro-nutrient deficiencies may occur in either of these categories [12].
Underweight	a state of suboptimal weight for one's age. It is determined by the anthropometric index of weight-for-age being two or more standard deviations below the international median value in well-nourished individuals. It approximates the state of mixed undernutrition.
Wasting	a state of suboptimal weight for one's height. It is determined by the anthropometric index of weight-for-height being two or more standard deviations below the international median value in well-nourished individuals. It approximates acute undernutrition.
Weather variability	here defined as changes in weather conditions and patterns across specific time periods, including differences in magnitude of these changes.

Chapter 1: Introduction

This chapter introduces and provides background to a doctoral thesis, which examines crop yield variation as an epidemiological risk factor for child undernutrition and mortality among subsistence farmers in rural Burkina Faso in the context of weather variability. This chapter contains the following sections:

1.1: thesis rationale,
1.2: policy and research context,
1.3: need for epidemiological evidence,
1.4: thesis structure.

1.1. Thesis rationale

The focus of this thesis is the relationship between weather, crop yields, child nutrition and health in a subsistence farming population of sub-Saharan Africa. It has particular relevance to the indirect health effects of climate change which arise from reductions in crop yields. The World Health Organization (WHO) and Intergovernmental Panel on Climate Change (IPCC) have proposed that undernutrition is the largest potential impact of climate change on child health [13–15]. It is likely to be borne disproportionally by subsistence farming populations in food-insecure regions [12,16]. However, a recent systematic review concluded that empirical evidence to substantiate the proposed impact in relation to subsistence farming populations is limited [12].

Processes leading to climate change that impact on child undernutrition could be mediated by a multitude of factors [12]. In subsistence farming populations the relationship between weather, crop yields, child undernutrition and mortality is suggested to be central to this pathway [12]. For the purpose of epidemiological analyses, in its simplified form this pathway can be conceptualized by the following relationships: "crop production – child undernutrition", "crop production – child mortality", "child undernutrition – child mortality" (Figure 1–1), which are unpacked in the following sections. In this thesis, I chose to focus on the variation in crop production (measured by crop harvest and yield) as a central element of this pathway and examine it as a risk factor for child undernutrition and mortality in the context of weather variability.

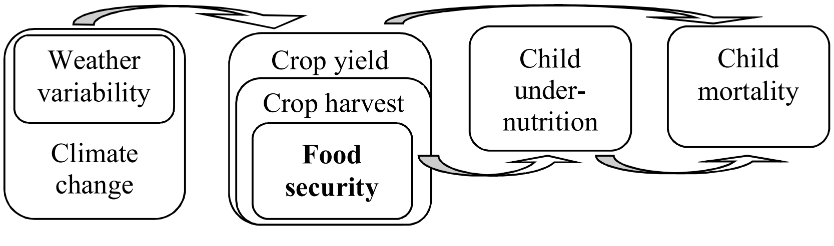


Figure 1—1. The proposed pathway of climate change impact on child undernutrition among subsistence farmers (image: adapted from Phalkey *et al* [12], reproduced under the CC BY-NC-ND 4.0 license).

(i) Crop harvest – central to subsistence farmers' food security

Cereal crop production is an important source of food supply globally. In developing countries it is estimated to provide over 50% of average individual food energy intake [17]. Around 50% of global agricultural land is estimated to be cultivated by family farmers, with some producing not more than is required to meet their subsistence needs [10,18]. The food security of these households to a large extent depends on their crop harvest. Crop harvests contribute to three of the four pillars of food security [4], which are: (1) food availability – sufficient quantity of food of adequate quality, which can be derived from the harvest, (2) food access – adequate resources to acquire appropriate foods, utilization, which can be derived from sales of agricultural produce, and (3) stability – access to adequate food at all times, which can be derived from stable and resilient harvest levels from one year to another [5,19,20]. They contribute less directly to the fourth pillar – food utilisation, defined as sufficient nutrient and energy intake, resulting from appropriate food preparation, diet, intra-household food distribution, feeding practices, good care, as explained below [4,5,19,20].

(ii) Crop harvest linked with child undernutrition and mortality

In subsistence farming populations household crop harvest, as a core component of household food security, could also be an important determinant of child nutrition and health. The conceptual framework of causes and consequences of child undernutrition, developed by the United Nations Children's Fund (UNICEF), recognizes household food insecurity as a determinant of child undernutrition [21]. Pathways linking crop harvest with child nutritional status in subsistence farming populations are illustrated in Figure 1–2. These pathways may be thought of as reflecting two groups of factors influencing child nutrition – (i) food availability and (ii) entitlement pathways, as originally conceptualised by Amartya Sen in analyses of factors contributing to famines [22,23]. Pathways relating to food availability reflect the fact that crop harvest deficits are likely to lead directly to lower levels of food availability for household consumption (pathway "1" in Figure 1–2) [22]. In contrast, pathways relating to (food) entitlements suggest that crop harvest deficits influence a household's ability to command access to food (their 'entitlements') through other routes, such as through opportunities for production, trade, and labour [22,23]. For example, the level of the household crop harvest determines household income from crop sales, and hence, the potential for expenditure on food, which subsequently determines food availability for consumption (pathway "2" in Figure 1–2) [24]. Income from crop sales may also be used for non-food expenditure, including assets and other resources required for effective food processing (e.g., cooking or food storage facilities, knowledge of nutritional requirements, time availability) as well as health care expenditure required for the maintenance of health and the ability to be productive and so maintain the nutritional status of the household members but also expenditure on any required treatment of undernutrition (pathway "3" in Figure 1–2) [24,25]. Furthermore, crop harvest levels across households contribute to the supply of crops on the market, thus, influencing their market price, and household income from crop sales as well as the affordability of purchasing crops on the market (pathway "4" in Figure 1–2) [24]. Crop harvest levels may also affect women's employment in agriculture with implications for intrahousehold decision making and resource allocation (particularly over food and health care), women's capacity for child care and feeding, and their own nutritional and health status, which is closely linked to child nutritional and health status (pathway "5" in Figure 1–2) [24].

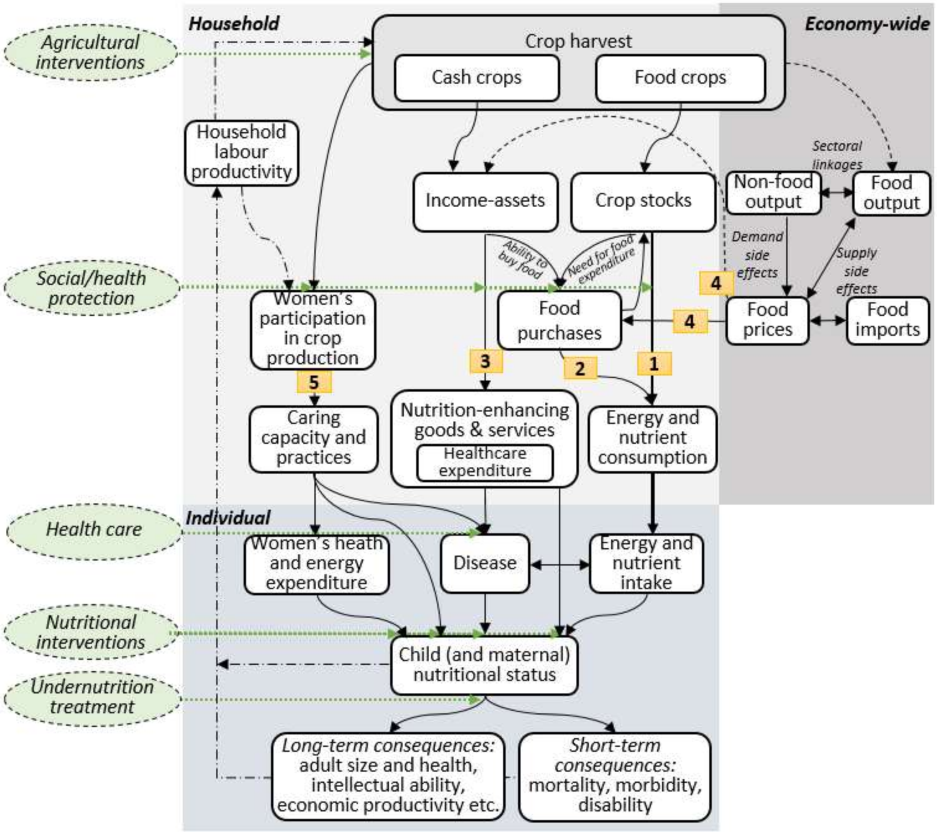


Figure 1—2. Links between household crop harvest, child nutritional status and mortality with potential intervention points (green, on the left) (based on Gillespie *et al* [24] **and Black *et al*** [21]**).**

Although numerous factors influence child nutritional status [21], econometric analyses suggest the relative importance of crop harvests in subsistence farming communities. Analyses over the period of 1970–1995 suggested that in sub-Saharan Africa and South Asia, two regions with the highest proportion of subsistence farmers, per capita food availability was the most important determinant of child undernutrition among all the recognized determinants that were analysed, including access to safe water, per capita national income, and democracy [26]. In the update of this analysis published in 2015, the authors repeatedly emphasized the importance of maintaining food production and supplies as a necessary, although not a sufficient condition, for the reduction of child undernutrition [27].

As shown in Figure 1–2, poor child nutritional status is further linked to increased risk of mortality. Undernourished children are more susceptible to infectious diseases and, particularly in cases of severe acute undernutrition, have a considerably higher risk of mortality [21,28]. Undernutrition is estimated to be responsible for over a fifth of the global disease burden in children under five years of age [21,29] and for 45% of all the 5.9 million deaths in children under five in the year 2015 [30]. With the importance of household crop harvest for food security and child nutrition in subsistence farming populations as suggested above, part of this burden might be related to insufficient household crop harvests.

(iii) Harvest and yield variation in the context of weather variability

The level of a household's crop harvest depends upon the acreage (area of land cultivated by the household) and the cultivated crop yield (amount of crop harvested per cultivated area of land). Changes in yield could be particularly sensitive to changes in weather conditions during the crop growing season. Hence, *annual yield variation* could be a useful measure for monitoring weather-related changes in the sufficiency of household crop harvest for adequate child nutrition and health in subsistence farming populations (especially in areas where yields may fluctuate below the levels that provide adequate food supply).

In sub-Saharan Africa over 95% of the agricultural land is not irrigated, relying on rainfall as the main source of water [31]. Thus, for rainfed agricultural systems, unfavourable annual changes in weather patterns (especially during crop growing season) pose a risk of low annual crop yield level, translating into lower household crop harvests, inadequate food/income from the harvests, and possible subsequent risk for child nutrition and health. It is estimated that annual climate variability globally accounts for 32–39% of the observed annual yield variability [32,33].

Climate change may affect crop yields through multiple links of weather and non-weather parameters, as illustrated in Figure 1–3. Changes in the regional weather patterns include effects on temperatures (changes in seasonal means, and the frequency of extreme temperatures) and on patterns of precipitation (timing, location, and amount of rainfall, seasonal changes, and changes in the frequency, duration, and intensity of dry spells, as well as increased intensity and frequency of extreme precipitation events), which may alter conditions for crop growth, influence insect, pest, pathogen and pollinator reproduction and survival, as well as affect human and livestock agricultural labour productivity [34,35]. Additionally, increased concentrations of atmospheric carbon dioxide and increased formation of ground level ozone (which is influenced by temperatures, sunlight, and emissions from plants of catalysing volatile organic compounds, as well as changes in other greenhouse gases) may affect crop yields by altering plant photosynthesis rates, water use efficiency, and grain formation [35]. With climate change, these factors are projected to change in a manner that suggests negative impact on agricultural yields in a number of regions with high prevalence of rainfed subsistence agriculture, such as West Africa [36,37].

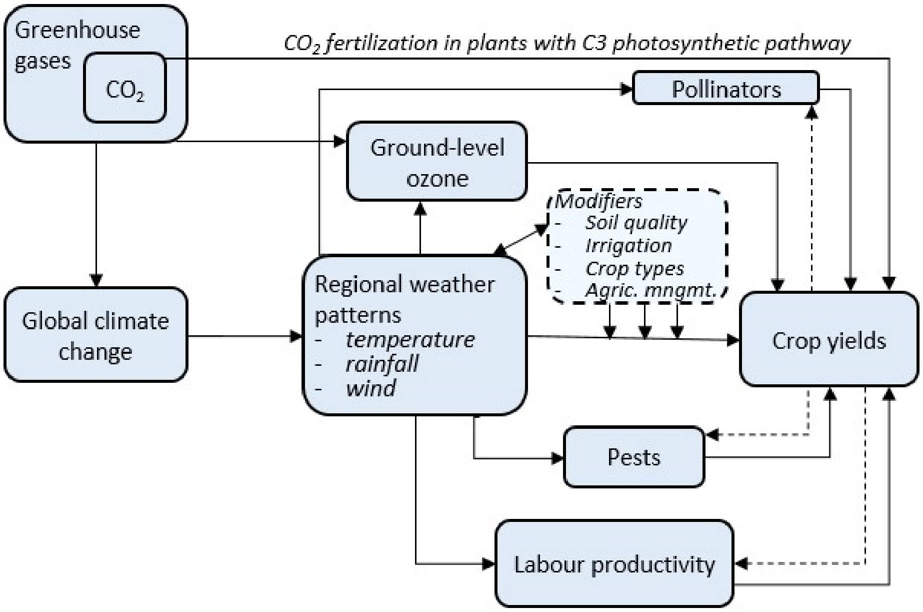


Figure 1—3. Links between climate change factors and crop yield (based on Myers *et al* [35]).

Therefore, it is reasonable to examine crop yield variation as a risk factor for child undernutrition and mortality among subsistence farmers in the context of weather variability.

1.2. Policy context

Elements of the pathway from climate change to child undernutrition through reduced crop yields have been granted notable attention in the international policy and research context, yet frequently in an isolated manner. The United Nations Sustainable Development Goals (SDGs), agreed for the period of 2015–2030 by 193 nation states, placed the goals of addressing preventable child deaths (SDG target 3.2), child undernutrition (SDG target 2.2), hunger and food insecurity (SDG target 2.1), low agricultural productivity (SDG target 2.3), and climate change (SDG 13) at the forefront of the global development agenda [38]. According to the progress report on the Millennium Development Goals (MDGs), which preceded the SDGs running over the years 2000–2015, considerable progress has been made in reducing the global proportion of undernourished children from 25% to 14% (figures relate specifically to children being underweight) and under-five child mortality rate from 90 to 43 deaths per 1,000 live births between the years 1990 and 2015 [39].

However, past work on the MDGs has been criticized for having too polarised and discrete a focus on separate goals and a lack of consideration for their interactions [40–43]. Such a focus may prove to be inefficient and even self-defeating. For example, it has been suggested that the progress made in reducing the proportion of undernourished children in developing regions could now be hindered and in some settings even reversed by climate change [44–49]. Modelling by Nelson *et al* suggests that climate change-related decline in food production may increase the number of underweight children worldwide by 24% by 2050 [47], while Lloyd *et al* suggested an additional 45% relative increase in child stunting in West Africa by the same year [49]. Based on these results, the IPCC and WHO listed undernutrition as the largest health impact of climate change in the 21st century [13–15].

In response to the criticism of having too discrete a focus on individual global development goals, emphasis has been increasingly made on the need for policy integration across sectors and for interdisciplinary research. This includes the integration of nutrition and health considerations into agricultural policies and programmes [20,40,50–52] as well as climate resiliency considerations of agricultural and health systems [53,54]. For example, nutritionally sensitive agricultural interventions are a recommended strategy for building resilience of poor populations in the face of food security threats, including weather-related shocks [19]. By operating through the determinants of health and nutrition such interventions are proposed to be effective in reaching poor populations as a result of their large scale implementation [19].

1.3. The need for epidemiological evidence

Despite the suggested importance of the pathway from climate change to child undernutrition through reduced crop production among subsistence farmers [13–15], strong empirical epidemiological evidence concerning this process is currently lacking [12]. The available estimates of climate change impact on child undernutrition produced by Nelson *et al* [47] and Lloyd *et al* [49] were based on global models and country-level data on calorie availability. These models were not capable of reflecting calorie availability in specific vulnerable groups at sub-national level, e.g., in subsistence farming populations [55]. Furthermore, food availability data in these models was derived from Food and Agriculture Organization (FAO) food balance sheets, which are criticized for their quality and do not account for subsistence food production [56].

To substantiate the proposed climate change impact on child nutrition and health through reduced crop yields in subsistence farming populations, empirical evidence is needed concerning associations along its key elements, i.e., from climate change and weather variation to crop yield variation, nutrition, and health outcomes [12]. Studies on the relationship of weather conditions with crop yield are available in most regions (e.g., in Africa [57–59], Asia [60–62], Europe [63–66], and North America [67–69]). By contrast, studies on the association of crop yield with child nutrition and health – specifically undernutrition and mortality – are few and often methodologically limited. These studies and their limitations are discussed in more detail in Chapter 2. To date, crop yield variation has not been adequately examined as a possible risk factor for child undernutrition and mortality.

In contrast with crop yield variation, climate change has been proposed [70], studied [71–73], and classified as a modifiable risk factor for human health in the WHO World Health Risks Report [74] and elsewhere [75]. This is important for informing the debate and policy considerations, and taking action on climate change mitigation.

However, a considerable fraction of the climate change impact on child undernutrition may no longer be addressed through mitigation, necessitating the adaptation to climate change [15]. Adaptation efforts can be designed by targeting key factors that mediate climate change impact pathways. Crop yield variation could be one such mediator in the pathway of climate change impacts on child undernutrition. More generally (beyond the context of climate change) it could be an important modifiable health risk factor among subsistence farmers. However, currently its presentation as a modifiable health risk factor is hampered by the lack of epidemiological evidence required to estimate the magnitude of its attributable health impact. Similarly, evidence of the effectiveness of agricultural programmes addressing crop yield levels for the reduction of child undernutrition is limited and inconclusive [19].

Hence there is a need for epidemiological studies of crop yield variation as a possible risk factor for child undernutrition, mortality, and other health outcomes in subsistence farming populations. Such epidemiological evidence could permit more accurate estimates of the potentially avoidable impact of crop yield variation on child nutrition and health under the current and future levels of weather variability.

1.4. Thesis structure

The remaining chapters of the thesis are structured as follows.

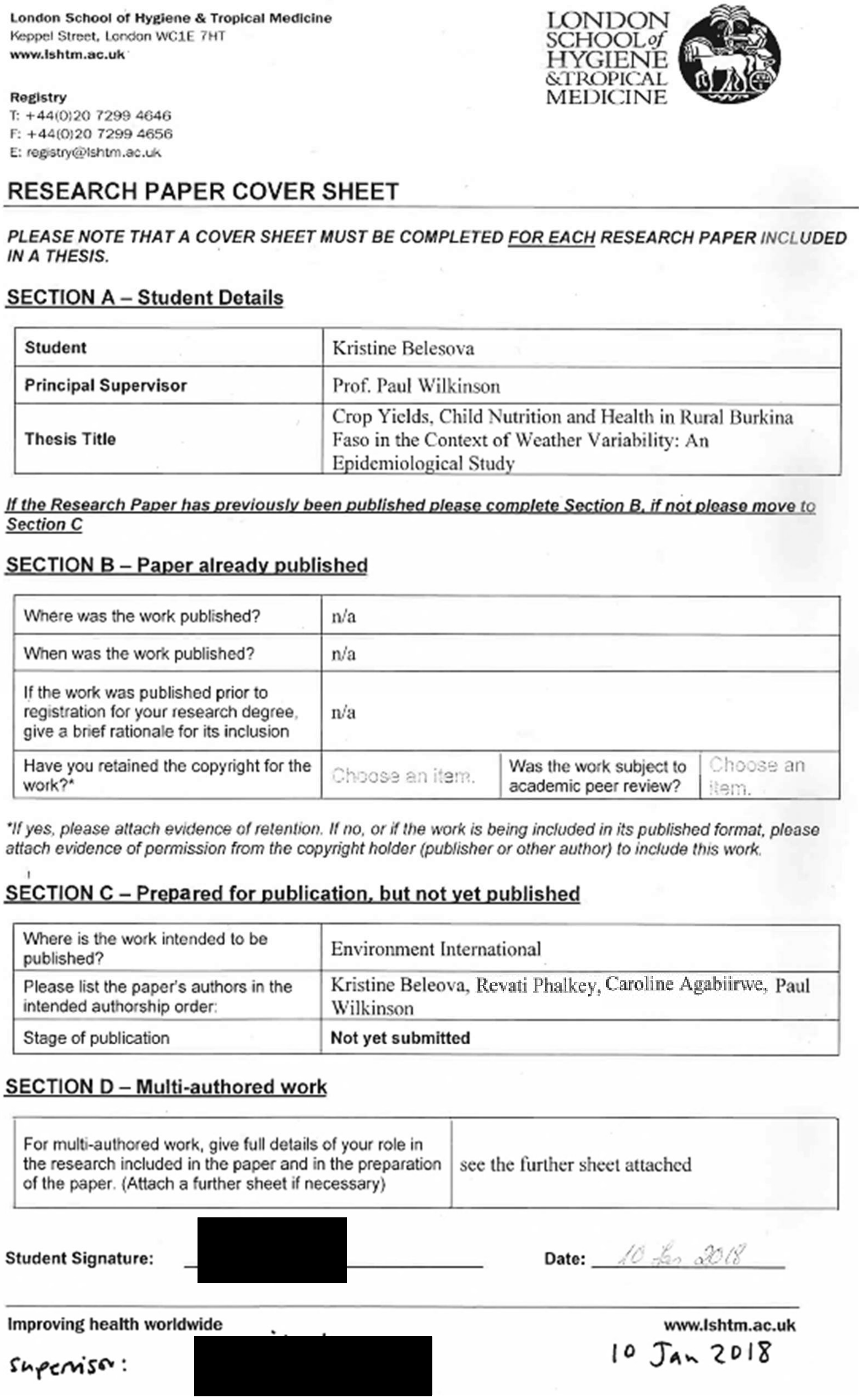
Chapter 2	critically summarizes the literature on existing empirical studies to inform focus of this thesis. This chapter contains the first research paper – a systematic review and assessment of evidence of drought impact as an extreme form of crop yield variation on child undernutrition in low- and middle-income countries. Further parts of the chapter summarize studies on the associations of crop yield/harvest with child undernutrition and mortality in low-income settings, identifying specific gaps in evidence.
Chapter 3	provides an overview of the thesis aim and objectives as well as background to the study setting.
Chapters 4–6	report studies of empirical research on the associations between child survival, nutritional status, crop harvest and yield as well as a model of child mortality burden attributable to low crop yields in the

	current and future climates. Each of these chapters contains an original research paper, its supplementary material (except for Chapters 2 and 6, whose supplementary material is placed in Annex), and commentary with additional discussion points highlighting methodological questions and implications of each paper in relation to the thesis aim and objectives.
Chapter 7	summarizes the findings of this thesis in relation to its aim, explains the contribution of the thesis to knowledge, and acknowledges limitations of this research. This chapter also discusses policy and research implications of the findings, suggesting direction for further research.

Chapter 2: Literature review

This chapter examines the literature to identify gaps in evidence relating to crop yield as a risk factor for child undernutrition and mortality in low- and middle-income countries in the context of weather variability and drought, and thus, to inform thesis objectives. In the initial stages of my research I was interested in potential impact of drought as an extreme form of crop yield variation related to adverse weather conditions. To examine the relevant evidence I conducted a systematic review of the literature on drought as a risk factor for child nutritional outcomes in low- and middle-income countries. This chapter starts with a research paper reporting results of the systematic review. However, as further elaborated below, after completing this review I concluded that this literature is dominated by often uncontrolled studies on the impacts of major drought events, including humanitarian emergencies that have limited relevance to less extreme variations in crop yields. I therefore selectively extended my literature research to focus on empirical observational studies relevant to individual links between crop yield or harvest with measures of (child) nutritional status and mortality, the results of which are also reported in this chapter.

2.1. Paper 1 *Systematic literature review*



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SECTION A – Student Details

Student	Kristine Belesova
Principal Supervisor	Prof. Paul Wilkinson
Thesis Title	Crop Yields, Child Nutrition and Health in Rural Burkina Faso in the Context of Weather Variability: An Epidemiological Study

If the Research Paper has previously been published please complete Section B, if not please move to Section C

SECTION B – Paper already published

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Where is the work intended to be published?	Environment International
Please list the paper's authors in the intended authorship order:	Kristine Beleova, Revati Phalkey, Caroline Agabiirwe, Paul Wilkinson
Stage of publication	**Not yet submitted**

SECTION D – Multi-authored work

For multi-authored work, give full details of your role in the research included in the paper and in the preparation of the paper. (Attach a further sheet if necessary)	see the further sheet attached

Student Signature: [redacted] **Date:** 10 Jan 2018

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Section D – Multi-authored work

I designed the systematic review and assessment of the evidence independently, conceived the idea of applying the Navigation Guide assessment methodology to the question of the review, and adapted its assessment instructions for this topic. Prof. Paul Wilkinson (thesis supervisor) reviewed the methods providing advisory input. I independently completed all steps of the review (design of the search strategy, literature search, record screening for inclusion, data extraction and analyses) and all steps of the assessment of the quality and strength of evidence, as per the Navigation Guide methodology (risk of bias assessment in individual studies, assessment of the quality of evidence, and assessment of the strength of evidence). In order for the systematic review to comply with the PRISMA guidelines (which recommend certain review and assessment stages to be undertaken by at least two authors independently) I invited and coordinated input of two co-authors Dr. Revati Phalkey and Ms. Caroline Agabiirwe to independently repeat and validate the following stages of the review. Dr. Revati Phalkey independently reviewed the identified papers for inclusion. Ms. Caroline Agabiirwe validated data extraction and independently completed the assessment of the risk of bias of individual studies. Prof. Paul Wilkinson independently assessed the quality and strength of the evidence, as well as helping to resolve any disagreement within the author pairs at all stages of the review. I prepared the first draft of the paper, reporting results of the analyses and their interpretation, edited the draft in response to comments by all co-authors, and prepared the paper for submission to *Environment International*, in line with the journal requirements.

Student signature: 10 Jan 2018

Supervisor signature: 10 Jan 2018

Paper 1:

Drought Exposure as a Risk Factor for Child Undernutrition in Low- and Middle-Income Countries: A Systematic Review and Assessment of Empirical Evidence

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Short title: Systematic Literature Review

Status: Prepared for submission to *Environment International*

Abstract

Background

Droughts affect around 52 million people globally each year, a figure that is likely to increase under climate change.

Objectives

To assess the strength of empirical evidence on drought exposure as a risk factor for undernutrition in children <5 years of age in low- and middle- income countries (LMICs).

Methods

Systematic review of observational studies published between 1990 and 2016 in English and reporting nutritional outcomes in children <5 years of age in relation to droughts in LMICs. The search was performed in the Global Health, Medline, Embase, and Scopus databases. We assessed the strength of evidence by type of undernutrition, following the Navigation Guide.

Results

23 studies met our inclusion criteria. Nearly half reported prevalence estimates in drought-affected conditions without comparison to unaffected conditions. These showed apparently high prevalence of chronic and mixed undernutrition and poor to critical levels of acute undernutrition. Only one study was judged to have low risk of bias, suggesting associations of drought exposure with children being underweight and having anaemia. Overall, the strength of evidence of drought as a risk factor was found *inadequate* for chronic and *limited* for acute, mixed, and micronutrient undernutrition.

Conclusion

Published evidence suggests high levels of all types of child undernutrition in drought-affected populations in low-income settings, but the extent to which these levels are attributable to drought has not been clearly quantified and may be context specific. The design of effective response strategies requires further evidence relating to the potential magnitude, timing, and modifying factors of drought impacts, and studies evaluating interventions.

Key words: climate change, disaster, drought, undernutrition, nutrition, evidence assessment

Introduction

Of all the natural hazards of 20th century, droughts have produced the greatest adverse impact on human populations [1]. On average, 52 million people globally have been affected by drought each year over the period of 1990–2012 [2]. The 2016 El Niño threatened the food security of 60 million people across East and Southern Africa, Central America and the Pacific with USD 3.9 billion requested for response provision [3,4]. According to the Intergovernmental Panel on Climate Change (IPCC), the severity and frequency of droughts is likely to increase in the 21st century in West Africa and the Mediterranean [5].

Through extreme weather events, such as droughts, and gradual changes in crop productivity, climate change is projected to increase the current global burden of child undernutrition by 20% by 2050 [6]. Undernutrition in early life is a challenge for child survival as well as health and productivity of the survivors. It was estimated to be responsible for 45% of the 5.9 million deaths in children under five in 2015 [7]. Adults, who were undernourished in childhood, have higher risk of chronic [8] and infectious [9] disease, compromised cognitive development [10], and lower economic productivity [11]. Therefore, it is particularly important to address the impacts of drought on nutrition specifically among children (conventionally below 5 years of age).

Although progress in decreasing the levels of global child undernutrition has been made since 1990, the rate of the progress has slowed [12]. Some argue, that progress may be reversed due to the effects of climate change and the increasing magnitude and frequency of extreme weather events such as droughts [13,6,14–17].

The global policy agendas on climate change, health, and disaster risk reduction acknowledge the possible impact of climate change and weather-related disasters on undernutrition [18–21]. It is recognised that development of effective preventative approaches, such as nutrition- and health- sensitive drought early warning systems, is necessary [22–25]. However, their development requires robust evidence characterising the possible magnitude and time-course of drought impacts on undernutrition, as well as the effect of potential modifying influences.

Evidence relating to the effects of drought on child undernutrition has not been reviewed in enough detail to be sufficient to address these questions. So far, two literature reviews have provided broad messages concerning the negative impact of drought on the nutrition of people of all ages [26,27]. Yet, the strength and quality of their synthesised evidence has not been systematically assessed. To inform the development of effective responses, it is essential to assess the robustness of the available evidence, identifying any methodological shortcomings for the improvement of future research.

In this paper, we review published (peer-reviewed) evidence on observational studies of undernutrition among children <5 years of age in relation to droughts in low- and middle- income countries (LMICs). Our objective was to answer the question: "Is drought exposure a risk factor for undernutrition in children <5 years of age in low- and middle- income countries?" We developed a "Participants", "Exposure", "Comparator", and "Outcomes" (PECO) statement as follows:

- Participants: humans, children <5 years of age
- Exposure: drought event(-s), as defined by the study authors
- Comparators: comparable population unexposed to a drought or the same population at a time when it was not exposed to a drought
- Outcome: any nutritional outcome continuous or categorical (e.g., identified using anthropometric indices or clinical signs)

We aimed to examine any evidence which relates to the magnitude and time-course of drought impacts as well as factors that may modify these effects. We assessed the strength of evidence on drought effects for each type of undernutrition (acute, chronic, mixed, and micronutrient), identifying methodological shortcomings, and providing recommendations for the improvement of the evidence base. Recently new approaches have been developed for systematic assessment of the quality and strength of observational evidence [28–30]. This paper adds to the emerging field of systematic reviews applying such assessment to the evidence of the health impacts of environmental factors and extreme events [28,31,32].

Methods

We followed the PRISMA Statement guidelines for systematic reviews.

Search methods

We searched the literature in Ovid Medline, Global Health, Embase, and Scopus, restricting our search to studies published in English with publication date from 1 January 1990 to 19 August 2016. In Embase and Medline, the search was limited to studies on humans (this filter was not available in other databases). We also screened reference lists of the two prior systematic reviews on the health impacts of drought [26,27]. The search was initially run on 12 December 2013, and updated on 19 August 2016.

The search strategy combined terms describing: drought exposure, possible nutritional outcomes, and LMICs as defined by the World Bank classification (see Supplementary Table 9–1 in Annex 3). The search strategy was constructed by KB, reviewed by PW and an expert in systematic review searches at the library of the London School of Hygiene and Tropical Medicine. We adapted the search strategy for each database by adding specific key words and synonyms identified in their thesauri and by adjusting the search syntax. Databases were searched by article abstracts, titles, key words, and headings (.mp).

Inclusion and exclusion criteria

Papers were included according to the following criteria: peer-reviewed full text reports of empirical observational studies published since 1990 in English, which reported nutritional outcomes such as acute, chronic, mixed, and micronutrient undernutrition but also other relevant anthropometric measures (Table 2–1) among children <5 years of age in relation to droughts (as defined by the authors), in LMICs (as defined by the World Bank in April 2013) (see Supplementary Table 9–2 in Annex 3). No inclusion criteria specifying study design was applied. We excluded non-peer reviewed publications and papers not reporting on empirical observational studies (e.g., commentaries, literature reviews), studies on non-human subjects, age groups other than children <5 years, exposures other than drought events (e.g., residence in arid and drought-prone areas), other health outcomes or measures of food security and intake, studies in high-income countries, published before 1990 or in languages other than English (see Supplementary Table 9–2 in Annex 3).

Table 2—1. The examined nutritional outcomes and their measures.

Nutritional outcomes	Measure	Abbreviation
Acute undernutrition	Weight-for-Height	Wt/Ht
	Middle-Upper Arm Circumference	MUAC
	Global Acute Malnutrition	GAM
Chronic undernutrition	Height-for-Age	Ht/Age
Mixed undernutrition	Weight-for-Age	Wt/Age
Micronutrient undernutrition	Vitamin (e.g., A, B, C) and micro-mineral (e.g., iron, iodine, zinc) deficiencies	n/a
Other	Length and height	n/a

Study selection and data extraction

Search results were combined and duplicates removed. Titles and abstracts were screened against the inclusion criteria (see Supplementary Table 9–2 in Annex 3), leaving studies for which inclusion was uncertain from these records for the full text eligibility review. The eligibility assessment was performed by KB and RP independently. Their independent judgements differed in 7% of the studies, and were resolved through discussion, and when necessary, consulting third reviewer (3% of studies) (PW). No exclusions were made based on the study quality to permit the assessment of any methodological shortcomings and the strength of evidence [33].

KB extracted data from the included papers into a pre-defined data extraction sheet. CA verified the extracted data against the full text papers. Any inconsistencies were resolved through discussion. Data extraction variables included country and location of the study, study aim, design, type of data used (primary or secondary), sample size, sampling strategy, secondary data sources, year(-s) of the drought, year(-s) of data collection, age of study subjects, outcome measures, outcome results, results on possible effect modification, drought description, drought exposure measures, authors' provided definition of drought, study context (setting and population), any interventions (existing or implemented in response to the drought).

Assessment of quality and strength of evidence

To assess the strength of evidence provided by reviewed articles, we followed the Navigation Guide framework [34,35]. The Navigation Guide provides guidelines on the assessment of the quality and strength of evidence and systematic synthesis of research in environmental health, including separate guidelines specifically for observational human studies [29,34,35]. The three stages of the assessment are: assessment of the risk of bias in individual studies, assessment of the quality of evidence, and assessment of the strength of evidence for each outcome type [34–36]. At each stage the assessment was performed by two authors independently (KB and CA at the first stage, KB and PW at the second and third stages), resolving any disagreement through discussion, and, if necessary, by consulting a third reviewer.

(1) Assessment of the risk of bias in individual studies

We assessed each study against 10 domains of the risk of bias as *low risk*, *probably low risk*, *probably high risk*, *high risk*, *not applicable*, or *unclear* using an adaptation of the methods described by Johnson *et al* (2014, 2016) [35,37] (see Supplementary Note 9–1 in Annex). To the criteria of Johnson *et al* we added the criterion of migration or survival bias for studies undertaken in circumstances when substantial movements of people or increased mortality might have occurred prior to data collection [35,37]. We adapted Johnson and colleagues' instructions [35,37] for the assessments of drought exposure and nutritional outcomes; we assessed as *probably low* (as opposed to *low*) the risk of bias from the involvement of governmental agencies and non-governmental organisations (NGOs). For the criterion of recruitment assessment we also took into consideration the consistency of sampling methods across subjects with different drought exposure levels.

(2) Assessment of the quality of evidence across studies

We assessed the quality of evidence across studies for each type of undernutrition (e.g., acute, chronic, mixed, micronutrient undernutrition) separately. Following the approach of the Navigation Guide, we rated the evidence as *high*, *moderate*, or *low*, initially assigning the rating *moderate*, and then considering adjustments based on the following factors: risk of bias across studies (assessed for each outcome type by presence of studies with *low* or *probably low* risk of bias by all domains of the assessment of the risk of bias in individual studies, except "blinding"), indirectness of evidence, imprecision, publication bias, size of the effect, dose response pattern, and whether confounding could minimise the effect. The assessment was performed as per Johnson and colleagues' instructions [35,37].

(3) Assessment of the strength of evidence across studies

We rated the strength of the body of evidence also by type of undernutrition, based on: quality of the body of evidence (i.e., rating from the previous stage of assessment), direction of effect (i.e., whether drought exposure suggests increased or decreased levels of undernutrition), confidence in the effect (likelihood of a new study changing our conclusion), any other attributes that may affect certainty, as explained by Johnson and colleagues [35,37]. No modification was made to the approach of the assessment of the strength of evidence [34–36].

Quantitative synthesis in a form of meta-analysis or a forest plot was not appropriate due to the diverse range of study designs and other methodological and contextual heterogeneity. Therefore, study findings, which included diverse measures of drought effect on child nutritional outcomes (Table 2–1), are summarised descriptively.

Results

Study selection

A flowchart of study selection is presented in Figure 2–1. Our search identified 5,781 unique records. Full text versions of 94 papers were reviewed for eligibility against the inclusion criteria. Of these, 71 were excluded: 20 for not examining the impacts of drought, 19 for not reporting nutritional outcomes, 19 for not being peer-reviewed articles on empirical studies, 11 for not reporting on children <5 years of age, one for being an earlier (repeated) published version of an already included study, and one for not reporting nutritional outcomes measured in the conditions with and without drought exposure separately (see Supplementary Table 9–1 in Annex 3). Six additional studies were identified from a lateral search of reference lists of the prior reviews [26,27]. 23 articles were included in the review.

Study context

The studies covered 19 different countries. Seventeen were single country studies, with a majority in Eastern Africa [23,38–43] and India [44–49] but also in Mali [50], Haiti [22], Afghanistan [51], North Korea [52], Indonesia [53], and Lesotho [54]. Four were multi-country studies [55–58] covering Eastern and/or Southern Africa. Eight studies examined rural populations [41,44,46,47,50,53,54,58], one an urban population [39], and one both rural and urban populations [38]. Others did not specify.

Seven studies were conducted in cases where high nutritional impact was already suspected. Authors described the situation as famine, based on official information or anecdotal evidence of high levels of undernutrition, starvation deaths, or increased mortality [38,40,42,48,50,54,56].

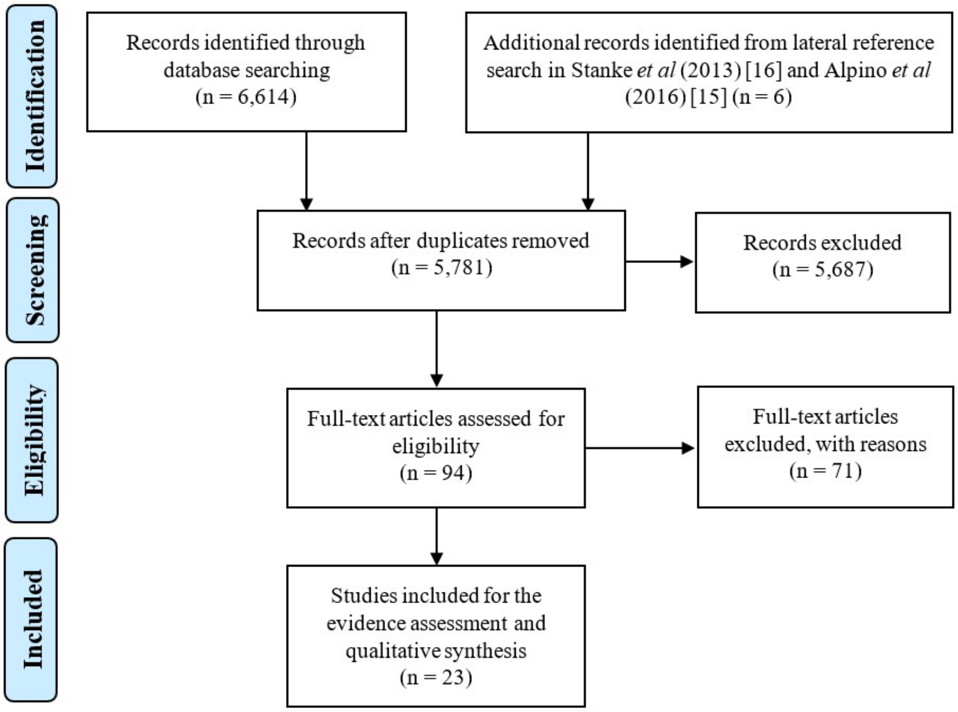


Figure 2—1. Flow chart of the study selection process and the number of records considered at each stage.

Contextual factors were not described by all articles but, when mentioned, emphasised the vulnerability of the study settings: the worst affected areas [40,44,46,48], drought-prone areas [38,44–46], high prevalence of Human Immunodeficiency Virus (HIV) [39,43,54,56], peak malaria time [48], poorest areas of the country [48,49,53,56], other agriculturally damaging disasters such as floods, wildfires, and hailstorms happening concurrently or shortly preceding the drought [52,53,56], economic decline or volatile commodity prices [38,53,56], government instability [38,53,56], war or armed conflict [40,51,56], and high baseline levels of the examined negative nutritional outcomes [44]. Only one study was conducted in a historical grain surplus production area [51].

Three studies mentioned nutritional programmes existing in their study areas prior to the drought [39,44,45], and ten interventions implemented in response to the drought, such as food distribution [38,40,41,51,54], nutrition [43,48,50], medical care and vaccination [40,50], or wider economic and food security management [57]. One article explicitly stated that the study was conducted in an area where no aid or assistance was received [51], others did not specify.

Study characteristics

The characteristics of the included studies are available in Table 2–2. All were observational studies that examined drought impact on nutritional outcomes of children <5 years of age in LMICs. The studies were published in English in peer-reviewed journals from 1990–2016 but conducted from 1984–2011, with the majority from 1990–2005. Study sample sizes ranged from 224 [41] to 149,386 [47].

Eighteen studies focussed on a single specific drought event [22,23,38–46,48–54,56] and five on multiple events [47,55,57,58]. Only two articles defined drought [45,47]. Most authors provided a descriptive reference to drought as an extreme event linked to low rainfall [23,44,45,47], low crop production and/or food insecurity [48,51,52,55–57], and a combination of the two [38,41,43,53,54], or as manifested by high staple crop prices [39].

In terms of the outcome measures, 15 studies examined measures of acute undernutrition [22,23,38,42,43,45–52,54,55,58], nine of chronic undernutrition [22,43,45,46,51,52,54], 12 of mixed undernutrition (also referred to as the state of being underweight) [22,41,43,45,46,48,49,53,54,56,57], and five studies of micronutrient (vitamins A, B, C and iron) deficiencies [44,46,47,49,53]. One study also examined infant length and height as anthropometric measures related to child nutritional status [39]. Most outcome data was collected in the first year of drought [22,23,39,41,42,44–47,49,52,53,55–58]. In five studies in the second year [38,40,50,57,58], one in the third year [51], one in the fifth year of the drought [48], and in two studies one and two years after the drought [38,49]. Fourteen studies were based on primary data [22,40–46,48–52,54]. Nine studies were based on secondary data, which were derived from a prior cohort study [39], from programme monitoring and evaluation [53], and from other surveys (Demographic and Health Surveys, Multiple Indicator Cluster Surveys, other government and NGO, and international organisation surveys) [23,38,47,55–58].

Study objectives, designs, and contexts varied (Tables 2–2 and 2–3). Depending on the design, studies had different potential to provide strong evidence of drought as a risk factor for child undernutrition (Table 2–3). Longitudinal and controlled or repeated (in conditions of different drought exposure levels) cross-sectional studies were generally viewed as providing stronger evidence (Table 2–3). Of all the reviewed studies there were six rapid emergency assessments [23,48,50,51,52,57] and four assessments of interventions addressing drought impacts [38,43,48,54].

Table 2—2. The reviewed study characteristics and key results.

Source	Location, drought year	Event characteristics	Context	Study period	Sample size	Age, months	Study design	Outcome measures	Key results
Arlappa *et al* 2011 [44]	India: Karnataka, Andhra Pradesh, Madhya Pradesh, Maharashtra, Orissa, Tamil Nadu, 2003	Most severely drought affected states	Rural, recurrent droughts, high vitamin A def. baseline levels	2003	3,657	12–59	Cross-sectional. With control	VAD (Bitot's spots)	- Higher prevalence of Vitamin A Deficiency (VAD) in drought affected areas than in unaffected areas (OR 2.0, 95% CI 1.6, 2.7)
Assefa *et al* 2001 [51]	Kohistan district, Faryab province, Afghanistan, 1998– 2001	Third consecutive drought year, loss of productive capacity, assets, livelihoods	Civil war, displacement, remote location, poor health care services	2011	708	6–59	Cross-sectional. No control	Wt/Ht, Ht/Age	- Under 5 Mortality Rate (U5MR) 5.9 (95% CI 2.0, 8.8) per 10,000 per day - Prevalence of stunting 63.7% (95% CI 58.6, 68.8%) with 34.6% severe stunting (95% CI 29.5, 39.7%) - Prevalence of wasting 7% (95% CI 5.9, 9.0%) with 1.1% (95% CI 0.2, 1.5%) severe wasting
Block *et al* 2003 [53]	Rural Java, Indonesia, 1997–1998	Severe drought linked to El Niño, low rainfall and harvest, food shortages, inflation	Economic crisis, inflation, political instability, wildfires, rural	1995–2005	107,753	0–36 and 0–59	Longitudinal	Wt/Age, blood Hb levels	- No effect on being underweight, adjusted for age & cohort effects - Increased prevalence of anaemia (from 52% to 68% or blood Haemoglobin (Hb) levels 10.36 *vs* 11.0 g/dl)
Carnell and Guyon 1990 [50]	Timbuktu region, Mali, 1983–1985	Drought across Sahel, reached famine in Mali, migration to urban areas	Rural, 30% nomads, rural-urban migration	1985	1,798	0–59	Cross-sectional. No control	Wt/Ht	- Prevalence of wasting 28%, severe wasting 0.5% - Prevalence of wasting was significantly higher in children 12-23 months of age (44% under -2SD and 12% under -3SD of the NCHS median) - Annual Crude Mortality Rate (CMR) of 39 per 1000 - people - Annual U5MR of 76 per 1,000 children<5y
CDC 1991 [22]	Nord-Ouest, Nord, Nord-Est, Artibonite, Centre, Haiti, 1990	Severe drought, low food supply, famine, most affected areas	Not described	1990	967	3–59.9	Cross-sectional. No control	Ht/Age, Wt/Age, Wt/Ht	- Prevalence of undernutrition: 40.6% chronic, 4.2% acute, 34% mixed

Table 2—2 (*continued*). The reviewed study characteristics and key results.

Source	Location, drought year	Event characteristics	Context	Study period	Sample size	Age, months	Study design	Outcome measures	Key results
Chotard *et al* 2010 [55]	Eritrea, Ethiopia, Kenya, Sudan, Somalia, Uganda, 2000–2006	Drought determined from records in nutrition surveys	Low rainfall areas, migrant, pastoralist, agriculturalist, mixed groups	2000–2006	897 (sub-) national nutrition surveys	0–59.9	Cross-sectional. Repeated in multiple sites and time points	Wt/Ht or GAM	- Drought years associated with higher prevalence of wasting, e.g., 5% increase in the drought year 2000 (p<0.001)
De Waal *et al* 2006 [38]	Ethiopia (national), 2002/3	A widespread drought during the main growing season affected 13.2 million people, relief requested	Drought prone, rural & urban, political inefficiency, environmental degradation, volatile prices	2004	4,816 households, no. of children not reported	1–59 (Ht/Age) 0–59 (deaths)	Cross-sectional. No control	Ht/Age, mortality	- Prevalence of stunting 57% - Higher prevalence of stunting in drought-affected areas than unaffected areas (numerical results not reported) - Mortality rates of 94 and 134 per 1,000 live births among infants and children respectively. Higher in drought-affected areas (than unaffected areas): infants 109(86), children 1–4y 55(39), <5y 158(121) per 1,000 life births. Adjusted drought effect not significant (p=0.8)
Gitau *et al* 2005 [39]	Maternal & child clinic in Lusaka, Zambia, 2001–2002	Regional drought, doubled the price of maize	Urban, in clinic, middle class, half of the mothers HIV+	2001–2003	429 0–1.5 months; 354 0–4 months	0–4	Longitudinal	length and weight	- Lower length Z-scores of infants exposed to drought-related maize price increase when measured at the age of 6 and 16 months, and those exposed *in utero* - No significant decline in weight Z-scores with price increase
Katona-Apte and Mokdad 1998 [52]	Kangwon, South: Hwanghae, Pyongan, Hamgyong, N.Korea, 1997	Historically one of the worst droughts, agricultural loss, food shortages despite aid	Tidal wave, hailstorm, flood, subsidy & ration system	1997	2,275	0–59	Cross-sectional. No control	Wt/Ht, Ht/Age	- Proportions of wasted (and severely wasted) children by age groups <6m, 6m-2y, 2-5y were: 16.7% (2.1%), 27.8% (5.8%), 14.8% (1.4%), stunted respectively: 0% (0%), 29.2% (10.9%), 38.6% (18.9%)
Kumar & Bhawani 2005 [48]	Baran district in Rajasthan, India, 1998–2002	5th drought year, loss of livestock & crops, migration, starvation deaths, economic loss	Rural, backward, semi-arid region; high malaria impact	2002 and 6 months later	n1=3206, n2=1775	0–59	Cross-sectional. Repeated in multiple time points	Wt/Age, Wt/Ht	- Prior to the interventions, prevalence of underweight children 63.4% (28.3% severe), wasting 27.3% (4.7% severe) - Prevalence of underweight children after the interventions 59.6% (26.1% severe)

Table 2—2 (*continued*). The reviewed study characteristics and key results.

Source	Location, drought year	Event characteristics	Context	Study period	Sample size	Age, months	Study design	Outcome measures	Key results
Kumar *et al* 2016 [47]	India (national), 2002–2004	Drought defined as a decrease in rainfall (Jun–Sep) below 75% of the long-term average at the district level	Rural, mostly rain-fed agriculture	2002–2004	149,386	0–59	Cross-sectional. Repeated in multiple sites and time points	Wt/Age, anemia	- Drought in the year of birth and year before birth was significantly associated with Wt/Age score (p<0.001), with being severely underweight (p<0.05) and somewhat with being moderately underweight (p<0.05 and p<0.10) - Drought in early life estimated to increase mean probability of being underweight by 2% - Drought in the year before birth (but not in the year of birth) was strongly associated with anaemia (Hb<11 g/dl) - Drought in the year of birth was significantly associated with infant mortality (rate ratio of 3.49, SD 1.44)
Lindtjørn 1990 [40]	Arero and Borana provinces, Ethiopia, 1984–1986	Severe drought and famine, 10% of the study population moved to relief shelters during the drought	Civil war, semi-nomadic pastoralists, sampled from food distribution sites	1985 & 1986	14,173 in 1985; 5,334 in 1986	12–59	Longitudinal	Mortality, Wt/Ht	- Mortality risk ratio peak drought *vs* post-drought: 2.26 (95% CI 1.89, 2.70); higher risk in famine relief shelters (p<0.01) - Prevalence of wasting during drought (*vs* no drought): Arero pastoralists 4.1% (3.3%), shelter populations 13.7% (5.7%), agropastoralists 3.7% (5.3%), Borana pastoralists 13.0% (3.1%), shelter populations 20.4%
Mahapatra *et al* 2000 [49]	Kalahandi district, Orissa, India, 1996 – 1997	Not described	Rural, backward, mostly landless agricultural labourers	1996–1997	751	0–59	Cross-sectional. No control	Wt/Age, Wt/Ht, Ht/Age, micronutrient def. (clin.sign)	- Prevalence of underweight children 57.1% (21.2% severe), wasting 27.9% (6.7% severe), stunting 41.8% (17.4% severe), marasmus 0.7%, clinical signs of protein-energy undernutrition 4.5% (among 1-5yrs olds), clinical signs of vit. B deficiency 5.8%, vit. A deficiency (Bitot's spots) 1.3% (among 2-5yrs olds), kwashiork absent
Mason *et al* 2005 [56]	Lesotho, Zambia, Mozambique, Swaziland, Malawi Zimbabwe, 2001/2	Severe food crisis, mild drought, increased food prices, famine deaths	HIV, poverty, market failure, recession, conflict, political disorder, flooding in Malawi	1992–2002	multiple surveys, number not specified	6–59 and 6–36	Cross-sectional. Repeated in multiple sites and time points	Wt/Age	- Prevalence of underweight children increased from 2001 (drought year) onwards, as compared to the preceding years, in all countries except Lesotho; highest increases: 5 to 20% in Maputo (Mozambique, 1997–2002), 17 to 32% in Copperbelt (Zambia, 1999–2001/2), 11 to 26% in Midlands (Zimbabwe, 1999–2002)

Table 2—2 (*continued*). The reviewed study characteristics and key results.

Source	Location, drought year	Event characteristics	Context	Study period	Sample size	Age, months	Study design	Outcome measures	Key results
Mason *et al* 2010 [57]	Ethiopia, Kenya, Uganda, Lesotho, Malawi, Mozambique, Swaziland, Zimbabwe, Zambia, 2001–03	Drought defined based on food security & production data reported by FAO	Long-term trends of improving situation in undernutrition	1992–2006	45 national nutrition surveys	6–59	Cross-sectional. Repeated in multiple sites and time points	Wt/Age	- Prevalence of underweight children higher in drought *vs* non-drought years: 24.7% *vs* 21.3%; p <0.05 in Southern African countries, and 28.0% *vs* 20.4% in the Horn countries - Food price weakly associated with children being subsequent underweight - Drought had greater impacts in the Horn countries
Mason *et al* 2010 [58]	Ethiopia, Kenya, Somalia, Sudan, Uganda, various over 2000–2006	Drought defined based on FAO food security & production reports	Rural	2000–2006	897 (sub-) national nutrition surveys	0–59	Cross-sectional. Repeated in multiple sites and time points	GAM	- Droughts correspond with spikes in Global Acute Malnutrition (GAM) and U5MR in all areas of study
McDonald *et al* 1994 [41]	Embu District of Eastern Province, Kenya, 1984	Severe drought, insufficient rains, crop failure, food shortage despite food aid	Small landholder agriculturalists producing both subsistence and market crops	1984	110	18–30	Longitudinal	Weight, Wt/Age	- Despite drought, body weight and Wt/Age scores increased smoothly for toddlers before, during, and after the drought with mean weight 9.5kg (SD 1.2kg), 10.2kg (SD 1.2kg), 10.8kg (SD 1.2kg) respectively and Wt/Age Z-score of -1.65 (SD 0.9), -1.58 (SD 0.9), -1.56 (SD 0.9) - No decline in toddler's growth-related weight gain
Moloney *et al* 2011 [42]	Southern Somalia, 2011	Crop failure, food insecurity, livestock mortality, increased cereal prices, widespread undernutrition	Not described	2011	not given	6–59	Cross-sectional. No control	GAM	- Prevalence of GAM was >20% in all 15 livelihood zones - In 11 of the 15 zones, GAM exceeded the famine threshold of 30% (range: 39–55%) - In 4 zones CMR exceeded the famine threshold of 2 deaths/10,000 population per day (range: 2.2–6.1) - U5MR ranged from 4.1 to 20.3 deaths/10,000/day
Mude and Barrett 2008 [23]	Marsabit, Samburu, Turkana, Baringo districts, Kenya, 2000	Drought defined by failure of rains and low forage availability	Arid districts, various communities	2000–2005	3,038: on average 50 monthly community aggregates	6–59	Longitudinal	MUAC (/Age)	- Drastic decrease in MUAC levels during the drought in 2000, leading to famine conditions (20% or more of children with Z-scores<-2). Trends in rainfall and forage availability rates may explain the increase

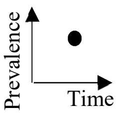
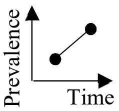
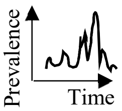
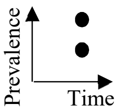
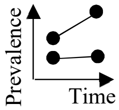
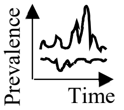
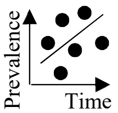
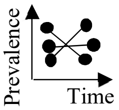
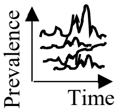
Table 2—2 (*continued*). The reviewed study characteristics and key results.

Source	Location, drought year	Event characteristics	Context	Study period	Sample size	Age, months	Study design	Outcome measures	Key results
Renzaho 2006 [54]	Quthing, Mafeteng, and Mohale's Hoek districts, Lesotho, 2002–2003	Dry cropping season hampered sowing, low harvest, food insecurity, severe water shortages	Adult HIV/AIDS prevalence 13–34%	2005	738	6–59	Cross-sectional. No control	Wt/Age, Wt/Ht, Ht/Age	- Prevalence of underweight children, stunting, and wasting was 15.6 (95% CI 8.8, 22.3)%, 33.7 (95% CI 25.7, 41.7)% and 10.9 (95% CI 6.5, 15.3)% among girls and 22.9 (95% CI: 15.1, 30.7)%, 38.5 (95% CI: 29.6, 47.4)% and 13.1 (95% CI 7.4, 18.8)% among boys, respectively - CMR was 0.8/10,000/day and U5MR was 3.2/10,000/day
Renzaho 2006 [43]	Tete province, Mozambique, 2002–2003	Drought due to insufficient rain, loss of productivity, food shortages, food insecurity	Food insecurity after several years of flooding, droughts, high levels of HIV	2004	874	6–59	Cross-sectional. No control	Wt/Age, Ht/Age, Wt/Ht	- Prevalence of wasting was 8.0 (95% CI 6.2, 9.8)%, underweight children 26.9 (95% CI 24.0, 29.9)%, and stunting 37.0 (95% CI 33.8, 40.2)% - CMR 1.23 (95% CI 0.71, 1.35), U5MR 1.03 (95% CI 0.71, 1.35) /10,000/day
Singh et al 2006 [46]	Jodhpur district, Rajasthan, India, 2003	Not described	Rural, desert drought prone area, weak economy, low coping capacity	2003	914	0–59	Cross-sectional. No control	Wt/Age, Ht/Age, vit. A, B, C def., anemia marasmus	- Prevalence of: wasting 39%, stunting 26%, vitamin deficiencies: A 0.7%, B 3%, C 0.1%, protein-energy undernutrition 44.4%, deficient calorie intake 76%, deficient protein intake 54%, prevalence of anaemia 30.5%
Venkaiah *et al* 2015 [45]	India: Chhattisgarh, Karnataka, Andhra and Madhya Pradesh, Rajasthan, Tamil Nadu, Maharashtra, Gujarat, Orissa, 2002–03	Drought defined as Jun-Sep rainfall <75% of long-term average in each state	Prone to recurrent droughts	2003	6,037	Pre-school	Cross-sectional. No control	Wt/Age, Wt/Ht, Ht/Age	- Across the states, prevalence of severe stunting ranged from 10.7–48.1%, severe wasting 0.9–7.4%, and underweight children 8.4–35.8%

Abbreviations: AIDS, Acute Immunodeficiency Virus; CI, confidence interval; CMR, crude mortality rate; FAO, Food and Agriculture Organization; HIV, Human Immunodeficiency Virus; Ht/Age, height-for-age index; GAM, global acute undernutrition; MUAC, middle-upper arm circumference; NCHS, National Centre for Health Statistics; VAD, vitamin A deficiency; UM5R, under 5 mortality rate; Wt/Age, weight-for-age index; Wt/Ht, weight-for-height index

[a] The study design in Lindtjørn 1990 was a prospective cohort with monthly repeated measurements of children's weight and height, results were presented as the prevalence of wasting at two points in time: during and after the examined drought event.

Table 2—3. Study designs and the strength of evidence they can potentially provide for an association.

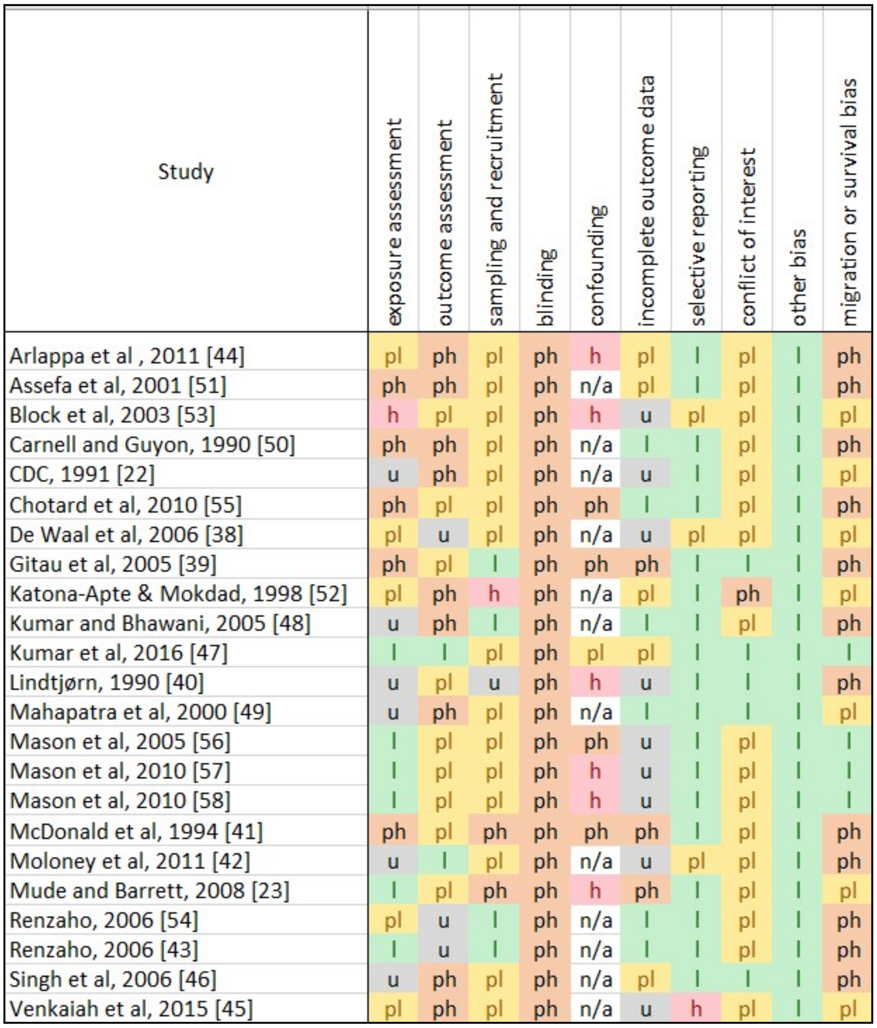
Study design	Cross-sectional		Longitudinal
	Single estimate in time	Repeated over time	
No control site	 11 studies: [22,38,42, 43,45,46,49,50–52,54]	 1 study: [48]	 6 studies: [23,40,41, 39,53]
One control site	 1 study: [44]	 0 studies	 0 studies
Multiple sites (with different exposure levels)	 0 studies	 5 studies: [47,55,56,57,58]	 0 studies

Risk of bias assessment in individual studies

The results of assessment in individual studies are summarised in Table 2–4 and synthesised across studies by type of undernutrition in Figure 2–2. Assessment summaries for each study are available in Supplementary Tables 9–4 to 9–26 in Annex 3.

We identified the lack of blinding, confounding, migration or survival, and outcome assessment as the most common sources of the risk of bias. None of the studies reported any attempt of blinding. Drought events received media coverage [48,50] and government announcements [38,45,53,54,56], thus, potentially raising awareness among the personnel performing outcome measurements about drought exposure status of the study subjects. Therefore, all studies (100%) were judged to have *probably high* risk of observer bias. Assessment of confounding was relevant only to the studies examining drought exposure–outcome associations, 11 of the 23 studies. Of these, 10 (91%) were judged to have *high* or *probably high* risk of bias, as they did not control for some of the key confounders (e.g., concurrent events posing risk to nutrition) or any confounders at all. Some studies were conducted in localised areas, after prolonged exposure to the droughts with likely outmigration and mortality of the most vulnerable prior to data collection. Twelve studies (52%) were judged to be *probably high* risk of migration or survival bias, as they did not account for the possible effects of these processes. Nine (39%) studies were judged to have a *probably high* risk of bias in the outcome assessment, as they may have underestimated undernutrition prevalence as a result of either using the National Centre for Health Statistics (NCHS) child growth reference, which (as opposed to the standards based on the World Health Organisation (WHO) Multicentre Growth Reference Study) does not represent ideal child growth [59,60], or by defining micronutrient deficiency based upon their clinical signs (as opposed to blood sample analysis) [61,62].

Table 2—4. Summary of the results of the risk of bias assessment in individual studies. Abbreviations: l, low risk of bias; pl, probably low risk of bias; ph, probably high risk of bias; h, high risk of bias; n/a, not applicable; u, unclear.



Study	exposure assessment	outcome assessment	sampling and recruitment	blinding	confounding	incomplete outcome data	selective reporting	conflict of interest	other bias	migration or survival bias
Arlappa et al , 2011 [44]	pl	ph	pl	ph	h	pl	l	pl	l	ph
Assefa et al, 2001 [51]	ph	ph	pl	ph	n/a	pl	l	pl	l	ph
Block et al, 2003 [53]	h	pl	pl	ph	h	u	pl	pl	l	pl
Carnell and Guyon, 1990 [50]	ph	ph	pl	ph	n/a	l	l	pl	l	ph
CDC, 1991 [22]	u	ph	pl	ph	n/a	u	l	pl	l	pl
Chotard et al, 2010 [55]	ph	pl	pl	ph	ph	l	l	pl	l	ph
De Waal et al, 2006 [38]	pl	u	pl	ph	n/a	u	pl	pl	l	pl
Gitau et al, 2005 [39]	ph	pl	l	ph	ph	ph	l	l	l	ph
Katona-Apte & Mokdad, 1998 [52]	pl	ph	h	ph	n/a	pl	l	ph	l	pl
Kumar and Bhawani, 2005 [48]	u	ph	l	ph	n/a	l	l	pl	l	ph
Kumar et al, 2016 [47]	l	l	pl	ph	pl	pl	l	l	l	l
Lindtjørn, 1990 [40]	u	pl	u	ph	h	u	l	l	l	ph
Mahapatra et al, 2000 [49]	u	ph	pl	ph	n/a	l	l	l	l	pl
Mason et al, 2005 [56]	l	pl	pl	ph	ph	u	l	pl	l	l
Mason et al, 2010 [57]	l	pl	pl	ph	h	u	l	pl	l	l
Mason et al, 2010 [58]	l	pl	pl	ph	h	u	l	pl	l	l
McDonald et al, 1994 [41]	ph	pl	ph	ph	ph	ph	l	pl	l	ph
Moloney et al, 2011 [42]	u	l	pl	ph	n/a	u	pl	pl	l	ph
Mude and Barrett, 2008 [23]	l	pl	ph	ph	h	ph	l	pl	l	pl
Renzaho, 2006 [54]	pl	u	l	ph	n/a	l	l	pl	l	ph
Renzaho, 2006 [43]	l	u	l	ph	n/a	l	l	pl	l	ph
Singh et al, 2006 [46]	u	ph	pl	ph	n/a	pl	l	l	l	ph
Venkaiah et al, 2015 [45]	pl	ph	pl	ph	n/a	u	h	pl	l	pl

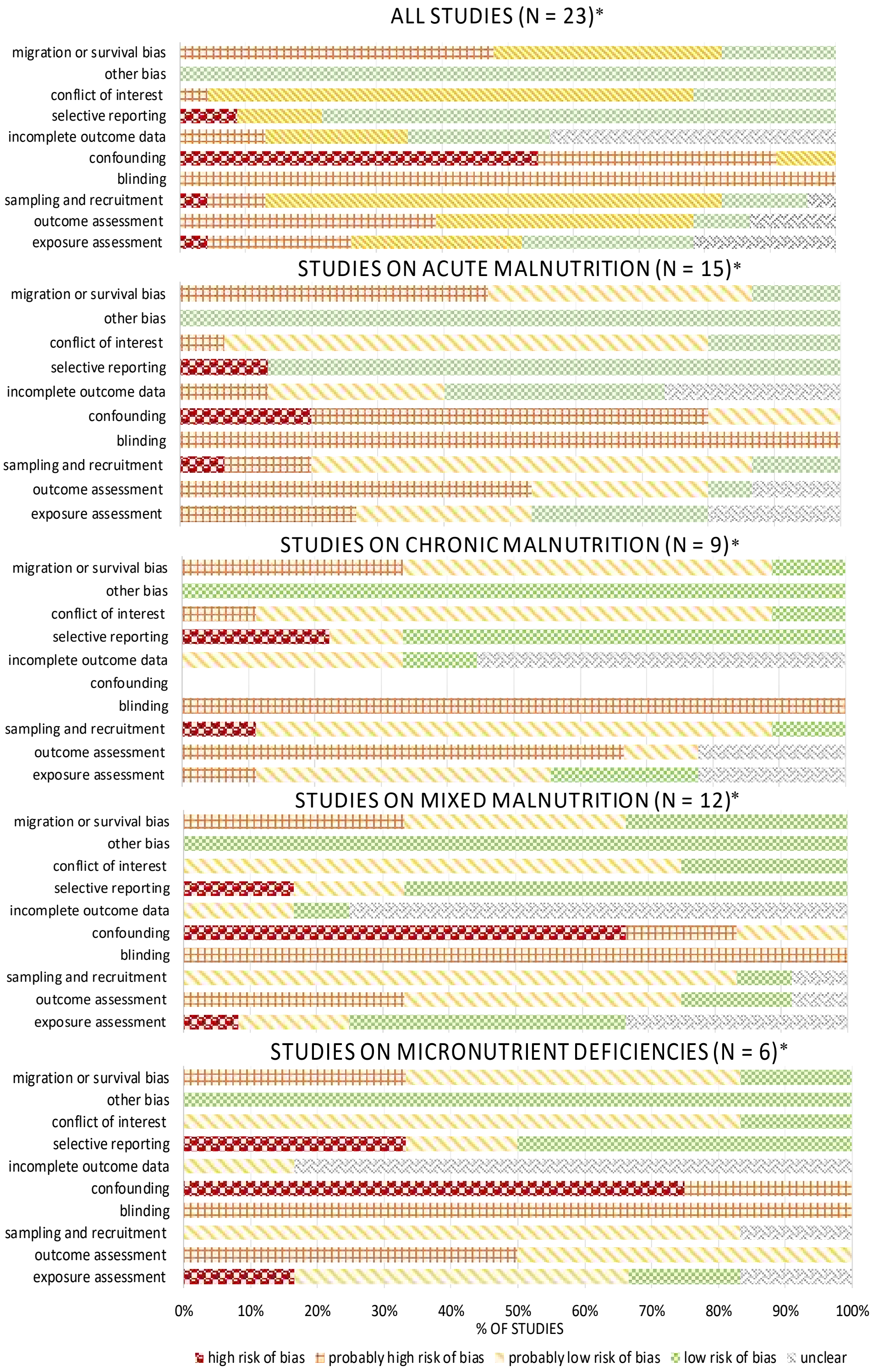


Figure 2—2. Synthesis of the risk of bias assessment across studies by type of undernutrition.

*The assessment of confounding was applicable and performed in 11 studies, therefore 100% corresponds to 11 studies in the overall summary, 5 in the summary of studies on acute undernutrition, 1 on chronic undernutrition, 6 on mixed, and 4 on micronutrient undernutrition.

Additionally, exposure assessment was frequently hampered by the limited information reported in the articles, making it difficult to assess the risk of bias in their exposure assessment. Six (26%) of the studies did not provide data on the drought exposure of their study populations or even a reference to a source providing such data. Further, six (26%) studies were judged to have *high* or *probably high* risk of bias in exposure assessment due to potentially biased measures or the lack of drought exposure ascertainment for their study area (e.g., only claiming drought exposure at the country level), which is important because droughts are often patchy phenomena and may not affect large territories uniformly.

Across all assessment criteria, only one study by Kumar *et al* (4%) was judged to have *low* or *probably low* risk of bias by all criteria (except blinding) [47]. Three studies (13%) did not report sufficient detail to assess their risk of bias by some of the criteria but were judged to have *low* or *probably low* risk of bias by all criteria (except blinding) where sufficient information was reported. The remaining 19 (83%) studies were judged to have *high* or *probably high* risk of bias by more than one of the assessment criteria.

Findings from the included studies

Key findings of each study are reported alongside study characteristics in Table 2–2.

(1) Acute undernutrition

Acute undernutrition was the most frequently examined type of undernutrition (15 studies). Four studies had designs that permitted the examination of its *association* with drought exposure, suggesting evidence for the association in the Horn of Africa [61,64], Ethiopia [40], and Kenya [23]. Yet all four studies were judged to have *probably high* or *high* risk of bias by at least two of the assessment criteria. The remaining eleven studies on acute undernutrition provided only single cross-sectional uncontrolled drought-time prevalence estimates. The prevalence of acute undernutrition (weight-for-height index Z-score< -2 Standard Deviations (SD)) ranged from 7% (95% CI 5.9, 9.0%) in a traditionally surplus grain producing area of war affected Afghanistan [51] to 28% during the second year of drought in Timbuktu, Mali [50], reflecting a *poor* to *critical* situation, by the WHO classification [63]. Attribution of acute undernutrition to drought exposure was limited.

(2) Chronic undernutrition

All (nine) studies on chronic undernutrition (or stunting) were based on uncontrolled single cross-sectional prevalence estimates during droughts, mostly indicating a *high* prevalence of stunting, as per the WHO classification [63]. The prevalence of stunting (height-for-age index Z-score< -2 SD) ranged from 26% in the Jodhpur district of India [46] to 63.7% (95% CI 58.6, 68.8%) in the Kohistan district of Afghanistan [51]. None of the studies were designed to examine the *association* of drought exposure with stunting.

(3) Mixed undernutrition

Of the twelve studies on mixed undernutrition (or the state of being underweight), five had designs that permitted the examination of its association with drought exposure. Of these, only the study by Kumar *et al* was judged of *low* or *probably low* risk of bias (by all criteria, except blinding), finding a statistically significant association of drought exposure in the year of birth and year before birth with weight-for-age Z-score in India [47]. The remaining four studies suggested mixed results concerning the association in Indonesia [53], Eastern Kenya [41], Southern Africa [57] and the Horn of Africa [58]. However, these four studies were judged to have (*probably) high* risk of bias by two or more criteria. The remaining seven studies on mixed undernutrition provided only single cross-sectional uncontrolled drought-time prevalence estimates. These studies reported drought-time prevalence of underweight children (weight-for-age index Z-score< -2 SD) ranging from 34% in Haiti during the first year of the drought [22] to 63.4% in Baran district of Rajasthan, India during the fifth year of drought [48]. According to the WHO [63], these prevalence levels are classified as *high* [63]. Yet, evidence of the *association* between drought exposure and being underweight was only provided by one study with a *low* risk of bias.

(4) Micronutrient undernutrition

Studies of micronutrient undernutrition were few (six studies), of which only two were designed to examine its *association* with drought exposure. Only the study by Kumar *et al* was judged to have *low* or *probably low* risk of bias (by all criteria except blinding), and suggested that there is evidence for an association between drought exposure in the year before child’s birth and a higher prevalence of child anaemia in India [47]. A longitudinal study suggested an association between anaemia and drought exposure in the year of birth in Indonesia [53] and one study with controlled cross-sectional design suggested greater vitamin A deficiency in severely drought affected *vs* unaffected areas of India [44], yet both were judged to be *probably high* or *high* risk of bias by four assessment criteria. The remaining two studies reported only uncontrolled drought-time prevalence of vitamin A, B, and C deficiency [52,55] in Indian states. Hence, only one study provided high quality evidence for the *association* of drought exposure with increased child anaemia in India.

(5) Other nutritional outcomes

A correlation of infant length (but not weight) Z-scores (measured at the age of 6 and 16 weeks) with drought-related maize price fluctuation, which the infants were exposed to *in utero*, was found in Lusaka, Zambia [39].

Time course of impacts

Most studies examined nutritional outcomes during the drought events. Two studies suggested that droughts may have longer-term effects. The study by Kumar *et al* (judged to be *low* or *probably low* risk of bias by all criteria except blinding), found that drought exposure at birth, *in utero*, and early life was associated with higher risk of being underweight until 5 years of age, i.e., also after the end of the drought event [47]. Furthermore, a study in Indonesia (*high* or *probably high* risk of bias by four criteria) suggested that the compound exposure to a drought and financial crisis led to a decline in child haemoglobin levels not only during the drought and crisis but remained below the pre-crisis level a year after the event [53].

Suggestive indication for effect modification

Although the reviewed studies did not formally examine the modification of drought effect on child undernutrition, their results suggested that differences in effect might be possible by age at exposure, sex, urban *vs* rural setting, level of HIV prevalence, and baseline levels of undernutrition.

The study by Kumar *et al* (*probably low* risk of bias except the criteria of blinding) suggested a stronger effect of drought exposure *in utero* than exposure in the year of birth on child haemoglobin levels in India [47]. Importance of age was further suggested by studies with *probably high* risk of bias, e.g., stronger effect on infant length retardation estimated in relation to exposure *in utero* as opposed to in the year of birth in Zambia [39] and no evidence for drought effect on weight-for-age index of toddlers *vs* negative effect on schoolchildren and toddlers' caregivers in Kenya [41]. The study in Indonesia with *high* or *probably high* risk of bias by four criteria suggested that compound exposure to a drought and financial crisis affected haemoglobin levels in boys significantly more than in girls [53].

The study by Kumar *et al* with *probably low* risk of bias (by all criteria except blinding) suggested a lower effect of drought on children being underweight in urban as opposed to rural areas of India [47]. By contrast, a study with a *probably high* risk of bias by two criteria observed greater drought-time deterioration in the underweight state of children in areas close to large towns as opposed to rural areas of Southern Africa, which could be linked to lower access to food aid or higher HIV prevalence in areas around towns [56].

Two studies with a (*probably*) *high* risk of bias by two criteria [62,63], suggested a significant interaction of HIV prevalence with the association of drought exposure and the risk of children being underweight in Southern Africa (but not in the Horn of Africa), observing a significant association in areas with high HIV prevalence but not in areas with low HIV prevalence. One of these studies also suggested the possible importance of baseline undernutrition levels, as child nutritional status deteriorated with drought more rapidly in areas with better than areas with worse baseline prevalence of underweight children in Southern Africa [56].

Quality of the body of evidence

A summary of the assessment of the overall quality of evidence by type of undernutrition is presented in Table 2–5. We downgraded the rating of the overall quality of evidence for acute and chronic undernutrition by the criteria of publication bias and the risk of bias across studies. We also downgraded the rating for chronic undernutrition by the criterion of indirectness to reflect absence of studies on its association with drought exposure (all studies reported only uncontrolled prevalence estimates). We upgraded the quality of evidence for acute undernutrition, due to the high magnitude of the possible effect (over two-times increase in the prevalence under drought exposure). The resulting overall quality of evidence rating was *low* for acute and chronic undernutrition and *moderate* for mixed and micronutrient undernutrition.

Table 2—5. Summary of the assessment of the quality and strength of evidence on drought as a risk factor for four types of child undernutrition in LMICs.

	Acute undernutrition (n=15)		**Chronic undernutrition (n=9)**		**Mixed undernutrition (n=12)**		**Micronutrient deficiencies (n=6)**	
	Rating	**Basis**	**Rating**	**Basis**	**Rating**	**Basis**	**Rating**	**Basis**
Quality of evidence assessment								
i. Downgrade considerations								
risk of bias across studies	-1	There is substantial risk of bias across most studies	-1	There is substantial risk of bias across most studies	0	Among all, one study with large sample judged to have low risk of bias	0	Among all, one study with large sample judged to have low risk of bias
indirectness	0	Anthropometric measures were appropriate outcomes, studies conducted in the population of interest, mostly direct measures of exposure	-2	None of the studies compared drought and non-drought periods directly	0	Anthropometric measures were appropriate outcomes, studies conducted in the population of interest, mostly direct measures of exposure	0	Anaemia was determined by measuring blood haemoglobin levels (however, vit A deficiency was examined using a surrogate measure – count of Bitot's spots), studies conducted in the population of interest, key studies used direct measures of exposure
inconsistency	0	Effect estimates often not clearly quantified, and variations likely because of differing contexts	0	Effect estimates often not clearly quantified, and variations likely because of differing contexts	0	Effect estimates often not clearly quantified, and variations likely because of differing contexts	0	Effect estimates often not clearly quantified, and variations likely because of differing contexts
imprecision	0	Mostly based on large surveys, but based on comparison across few settings or years	0	Mostly based on large surveys, but based on comparison across few settings or years	0	Mostly based on large surveys, but based on comparison across few settings or years	0	Mostly based on large surveys, but based on comparison across few settings or years
publication bias	-1	Most studies examined severe events, not reflective of the full range of drought events occurring	-1	Most studies examined severe events, not reflective of the full range of drought events occurring	0	Severe events examined <50% of the studies; publication bias possibly insufficient for downgrading	0	Severe events examined in 50% of the studies; publication bias possibly insufficient for downgrading
ii. Upgrade considerations								
large effect magnitude	1	Effect magnitude was over 2 (but not 5) times increase in the outcome prevalence	0	No effect estimates were available	0	Effect magnitude was below 2 times increase in the outcome prevalence	0	Effect magnitude was below 2 times increase in the outcome prevalence
dose response	0	Not reported in individual studies. Difficult to compare across studies	0	Not reported in individual studies. Difficult to compare across studies	0	Not reported in individual studies. Difficult to compare across studies	0	Not reported in individual studies. Difficult to compare across studies
confounding minimizes effect	0	No evidence found to suggest that possible residual confounders would reduce effect estimate	0	No evidence found to suggest that possible residual confounders would reduce effect estimate	0	No evidence found to suggest that possible residual confounders would reduce effect estimate	0	No evidence found to suggest that possible residual confounders would reduce effect estimate

Table 2–5 (*continued*). Summary of the assessment of the quality and strength of evidence on drought as a risk factor for four types of child undernutrition in LMICs.

	Acute undernutrition (n=15)		**Chronic undernutrition (n=9)**		**Mixed undernutrition (n=12)**		**Micronutrient deficiencies (n=6)**	
	Rating	**Basis**	**Rating**	**Basis**	**Rating**	**Basis**	**Rating**	**Basis**
iii. Summary of the quality assessment								
overall quality of evidence start: moderate	Low	Moderate + (-1) + (-1) + (1) = low. Downgrading/upgrading changed the quality from moderate to low	Low	Moderate + (-1) + (-2) + (-1) = low. Downgrading changed the quality from moderate to low	Moderate	Moderate + (0) = moderate. There were no upgrades or downgrades to change the quality from the initial rating	Moderate	Moderate + (0) = moderate. There were no upgrades or downgrades to change the quality from the initial rating
summary of findings	n/a	Usually higher prevalence of wasting found during droughts, but not always clear	n/a	Usually prevalence of chronic undernutrition during droughts was high, but not always clear	n/a	Higher risk of being underweight with early life drought exposure	n/a	Higher prevalence of anaemia and vitamin A deficiency found with drought
Strength of evidence assessment								
quality of evidence	n/a	Low	n/a	Low	n/a	Moderate	n/a	Moderate
direction of effect estimates	n/a	Direction as expected (more wasting in drought)	n/a	Direction unclear, as none of the studies compared drought and non-drought conditions directly	n/a	Direction as expected (more children being underweight in drought)	n/a	Direction as expected (more anaemia/vitamin deficiency in drought)
confidence in effect estimates	n/a	Effect estimates uncertain, often uncontrolled, and relate to varying contexts. Difficult to compare across studies, therefore. New studies might show different estimates.	n/a	Effect estimates uncertain, often uncontrolled, and relate to varying contexts. Difficult to compare across studies, therefore. New studies might show different estimates.	n/a	Effect estimates uncertain, often uncontrolled, and relate to varying contexts. Difficult to compare across studies, therefore. New studies might show different estimates.	n/a	Effect estimates uncertain, often uncontrolled, and relate to varying contexts. Difficult to compare across studies, therefore. New studies might show different estimates.
other aspects	n/a	Drought event characteristics, contextual factors, including population exposure level and vulnerability, any preventative or humanitarian response vary across studies and make interpretation less certain and less clear.						
overall strength of evidence	Limited	Positive association of drought with increased prevalence of acute undernutrition is likely. Lack of rigorous control and comparability across studies means quantitative estimates can be interpreted in only the broadest terms.	Inadequate	The available evidence is too indirect (and often lacking direct control) to enable robust interpretation. Evidence weakly suggestive but not clear. Further studies are needed to assess the effect.	Limited	Positive association of drought with increased prevalence of mixed undernutrition is likely, however, current evidence is limited and effect estimates may change with further studies, particularly as different temporal aspects of the association are examined.	Limited	Positive association of drought with increased prevalence of anaemia, but again difficult to compare studies given variations in context. Effect estimates may change with further studies. Evidence on the effect on other micronutrient deficiencies was limited (vitamin A deficiency) or missing.

Strength of the body of evidence

A summary of the assessment of the strength of evidence is also presented in Table 2–5. We made the following considerations for the strength of evidence. Quality of the body of evidence (as concluded above): *low* for acute and chronic undernutrition, *moderate* for mixed and micronutrient undernutrition. Direction of effect estimate: increasing for acute, mixed, and micronutrient undernutrition, but no effect estimates were available for chronic undernutrition. Confidence in effect estimates: effect estimates were uncertain and often uncontrolled; new studies might show different estimates. Other compelling attributes of the data that may influence certainty: drought event characteristics, contextual factors, population vulnerability, and drought response may make the interpretation less certain and less clear. We concluded that there was limited evidence for drought exposure as a risk factor for acute, mixed, and micronutrient undernutrition among children <5 years of age in LMICs and inadequate evidence for drought exposure as a risk factor for chronic undernutrition.

Discussion

Summary of evidence

Our evidence review of observational studies on undernutrition among children <5 years of age in relation to periods of drought in LMICs suggests that the evidence base is not sufficiently robust to provide quantitative estimates of attributable impacts. Only one study, by Kumar *et al* was judged of *low* or *probably low* risk of bias by all criteria of individual study assessment (except the criteria for blinding, which was not implemented by any study), suggesting an adverse effect of early life drought exposure on children being underweight and having anaemia during and after the drought events [47]. By outcome type, the overall strength of the evidence for acute, mixed, and micronutrient undernutrition was judged to be *limited* due to the risk of bias, lack of estimate comparability across studies, and likelihood that further studies could show different results. For chronic undernutrition the overall strength of evidence was *inadequate*, as the available evidence was too indirect (and often lacked direct control in conditions without drought exposure) to enable robust interpretation; further studies are needed to assess the effect.

Limited and *inadequate* evidence does not suggest that drought exposure is not a risk factor for child undernutrition in LMICs, but reflects the lack of robust research, much of which was undertaken in challenging circumstances for epidemiological surveillance and substantial heterogeneity in contexts.

Nonetheless, these studies are valuable in highlighting the high prevalence of undernutrition in LMICs during the examined drought events across the entire range of years from 1984 to 2010. According to the WHO, these levels require urgent response in the short term [63] but also the development of preventative strategies in the long term. What remains uncertain is the extent to which the observed levels of child undernutrition are attributable to drought exposure as opposed to other contextual factors and concurrent events.

Development of effective preventative response strategies must be based on robust evidence on the potential magnitude and timing of the effects, as well as their modifying factors. The results of our review suggest that drought exposure may be associated with a higher risk of undernutrition not only during the drought but also several years after the event [47]. Our findings also suggest possible modification of drought effect by such factors as sex, age, urban *vs* rural setting, baseline health and nutritional status of the exposed. However, further investigation of these aspects, based upon methods permitting time-course and effect modification analyses, is required to acquire comprehensive and robust evidence relating to who, when, and where may require targeted support the most.

To facilitate the improvement in the quality and robustness of further studies on this topic, we summarise our identified methodological shortcomings of the reviewed studies and provide corresponding recommendations.

Identified methodological shortcomings & recommendations

A key limitation of the reviewed studies was the lack of robust study designs that would permit attribution of drought impacts on child undernutrition. The majority of the studies were based upon a single set of cross-sectional data without control. There is a greater potential to provide evidence of the cause–effect association on the part of studies that used a control population or examined several estimates in time, and also by longitudinal studies. However, most of these study designs (with one exception [47]) did not permit the elimination of the risk of confounding to discern the proportion of child undernutrition that was attributable exclusively to the drought event as opposed to any potential concurrent events, e.g., war or financial crisis, that could also have had a simultaneous negative effect on child nutrition during the examined drought events. Many of the reviewed studies with these designs had further shortcomings, such as the (almost inevitable) lack of blinding, the limited assessment of possible survival and migration bias, and poor control for confounding, all of which often limited the robustness of their findings. Well-designed studies, based on longitudinal data and which minimise the risk of survival and migration bias whilst comprehensively controlling for confounding, are required.

The robustness and comparability of the reviewed studies was also subject to limitations of outcome assessment methods. The prevalence estimates of child undernutrition could have been underestimated in studies that used the NCHS growth reference in the assessment of anthropometric indices and studies that used clinical signs to detect micronutrient deficiency [60,61,62]. Furthermore, many studies did not report their data quality control and cleaning procedures, which are required for the assessment of the risk of bias. To acquire accurate undernutrition prevalence estimates, future studies should use the WHO Child Growth Standard in the assessment of anthropometric indices [60] and blood sample micronutrient measurements [61,62], as well as report data quality control and processing procedures.

Furthermore, evidence of the reviewed studies was limited by shortcomings in the exposure assessment methods, particularly the lack of drought definition and exposure justification with data on relevant, direct, and geographically accurate proxy measures of drought. Drought typology ranges from meteorological, agricultural, and hydrological, to socio-economic droughts, which reflects the diversity of their underlying causes [64]. Droughts are slow onset events, which develop over periods of time, and have no visual or structural boundaries with their impacts lasting long after the physical drought conditions are over [1]. The use of an operational definition of drought which identifies its onset, severity, and termination [64,65] (e.g., Standardized precipitation index, Palmer drought severity index [1,64,66]), could facilitate analyses of temporal aspects of drought impact and improve the comparability of results across studies.

To inform the design of effective preventative response strategies (e.g., early warning systems), models forecasting the nutritional impacts of droughts could be explored. Exposure metrics for such models could be selected based on their capacity to predict the nutritional impact with a lead-time sufficient for response implementation. Only one study included in this review attempted predictive modelling that could be used for the design of a nutrition-focussed drought early warning system [23].

Limitations of the review

We did not search for publications in languages other than English nor in grey literature. Given the focus of this review on the quality and strength of peer-reviewed evidence, grey literature was not considered eligible for our assessment.

Conclusion

The strength of evidence on drought as a risk factor for undernutrition among children <5 years of age in LMICs is *limited*. Nonetheless, studies suggest that there are apparently high and critical levels of child undernutrition in vulnerable settings during droughts, indicating the need for short-term response, and the development of preventative strategies in the long-term. The latter requires improved evidence of the magnitude of the drought-attributable fraction of child undernutrition, timing of drought impacts, influence of vulnerability and other potential modifying factors, and (in time) intervention studies.

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2.2. Implications of Paper 1 *Systematic literature review*

The systematic review included in the preceding section mainly provided evidence concerning the impact of severe droughts on child undernutrition in low-income settings. The majority of these events occurred simultaneously with other events, e.g., wars, other natural disasters, economic crises, and political instability that could have also contributed to child undernutrition identified at the time of the drought. In such cases, the study design did not allow the proportion of child undernutrition that was attributable exclusively to the drought event to be discerned. Attribution of the observed levels of undernutrition to the droughts was also constrained by limitations of the study designs, many of which were based on uncontrolled prevalence studies. For the research needs of this thesis, I concluded that the literature covered by this review mostly addressed extreme drought events (often classified as famines) and had limited relevance to more typical year to year variation in weather patterns and crop yields.

After the above-presented systematic review was completed, two important meta-analyses of survey data were published on drought effects in Ethiopia over the period of 2000–2013 [76,77]. These meta-analyses suggested greater impact on child wasting and mortality in areas with moderate levels of drought and minimal levels of food insecurity as compared to areas with severe drought and high food insecurity [76,77]. A possible explanation was that areas with minimal food insecurity or drought may not attract the attention of aid agencies and the government, leaving negative nutritional and health impacts unaddressed [76,77]. A study in Burkina Faso also observed that moderate rainfall shocks during crop growth season had a similar magnitude of effect on child stunting as severe shocks [78].

Furthermore, most studies included in the systematic review, presented in the preceding section, did not report on the type of the drought they examined. The term *drought* can be used to refer to a meteorological drought (related to departures in precipitation from its norm), hydrological drought (related to deficiency in surface and subsurface water supplies), groundwater drought (related to deficiency in groundwater recharge, levels, and discharge), agricultural drought (linked to agricultural impacts and often expressed in terms of soil moisture required for specific crop types), and socio-economic drought (expressed as a shortage of water in terms of its supply and demand) [79]. Not all of the drought types are necessarily related to weather variation. Therefore, the extent to which results of this literature are relevant to the context of less extreme variations in crop yields and weather is unclear.

Overall, the systematic review addressed only to a limited extent the empirical evidence that is required to substantiate the proposed climate change impact on child undernutrition through reductions in crop production. I therefore extended my literature research specifically to focus on the link between crop yield variations and measures of child nutritional status. Because the drought literature also suggested an impact on mortality, I included studies on the link between yield variations and child mortality – an outcome that was not part of the search strategy for the systematic review reported above.

2.3. Observational studies relating to crop yield variation as a risk factor for child undernutrition and mortality

According to a recent systematic literature review of climate change impacts on child undernutrition in subsistence farming populations by Phalkey *et al*, these impacts mainly operate through reductions in crop yield [12]. As outlined in the section 1.1, in its simplified form this impact pathway can be characterised by the following relationships: “crop production – child undernutrition”, “crop production – child mortality”, “child undernutrition – child mortality”. Evidence of the impacts of climate change and weather variation upon crop yields has been comparatively well-researched and suggests that annual climate variability globally accounts for 32–39% of the observed yield variability [32,33]. Similarly, the association of child undernutrition with mortality has been extensively researched and systematically reviewed and indicates a ten-fold increase in the risk of mortality among severely underweight and wasted children and a four-fold increase among severely stunted children [21,80]. Of all anthropometric measures of nutritional status, the strongest predictor of child mortality is Middle-Upper Arm Circumference (MUAC) [81,82]. MUAC values <115 mm, indicate severe acute undernutrition, and 115–125 mm, moderate acute undernutrition among children 6 month–5 years of age [81,82]. These MUAC cut-off values are used in screening for undernutrition treatment [81,82].

There is far less evidence of the link between annual crop yield variations and child undernutrition/mortality. The systematic review by Phalkey *et al* concluded that evidence relating to the associations of child undernutrition (mainly stunting) with weather, climate, and crop yield variables was limited. The identified studies were mostly cross-sectional, lacked comprehensive control for confounding variables, and relied on secondary data collected for other purposes [12]. Evidence of the association between annual crop yield variations and child undernutrition/mortality is key to the impact pathway of climate change upon child nutrition/health [12] and is central to the focus of this thesis.

Here, I chose to critically summarize empirical observational studies that examined the associations between measures of crop yield or harvest and child undernutrition and/or mortality in low-income settings. These studies were identified through searches in Medline and Google Scholar as well as by reviewing references in Phalkey *et al* [12]. I performed the searches in September 2016 and completed an update in November 2017 using the search terms (“mortality” OR “survival” OR “deaths” OR “malnutrition” OR “undernutrition” OR “nutrition”) AND (“yield” OR “harvest” OR “grain” OR “agricultural production” OR “drought”) AND (“child” OR “children”). I chose to focus the search on crop yield and harvest as measures of the quantity of crop produce, as opposed to crop diversity. Studies of crop diversity and child nutrition have been systematically reviewed elsewhere [83]. Changes in crop diversity are not central to the focus of this thesis, as they are unlikely to be related to annual variations in weather conditions.

The identified studies are summarized in Table 2–5. The studies were conducted mostly in Africa and South Asia and broadly fall into three sets of analyses: (1) household-level cross-sectional analyses of the associations between child nutritional status and proxies of household crop harvest; (2) area-level analyses of the associations of child nutritional status and mortality with spatial variation in proxies of crop yield; (3) analyses of child nutritional status and mortality with temporal variation in crop yield.

Table 2—6. Summary of studies on the links of crop harvest or yield with child nutritional status and mortality.

Source	**Country**	**Exposure measure**	**Level of analysis**	**Study design**	**Outcome measure**	**Sample size**	**Age, years**	**Key results**
I. Household-level cross-sectional studies on child nutritional status and household crop harvest proxies								
Arakesh *et al*, 2011 [84]	Rwanda	born in area affected by crop failure; household-level crop failure (departure from 3-year average yield)	province and household	controlled comparison over time	Ht/Age	1,615 children	<5	- 0.41 SD lower Ht/Age Z-scores for girls (but not boys) who were born in a year of crop failure, with greater decrease in girls from poor households
Brentlinger *et al*, 1999 [85]	El Salvador	area of land cultivated	household	cross-sectional	Ht/Age	761 children	<5	- Smaller area of redistributed land cultivated associated with higher risk of stunting (OR for stunting per additional hectare of cultivated land 0.64, 95% CI 0.44, 0.93)
Kaufman, 2008 [86]	Northern Laos	rice harvest	household	cross-sectional	Ht/Age	600 ('97), 892 ('01) children	<5	- Rice yields were not statistically significantly associated with child stunting (*article did not report numerical estimates*)
Kumar *et al*, 2015 [87]	Zambia	total quantity and income from agricultural production	household	cross-sectional	Ht/Age, Wt/Ht	3,340 households	0.5–5	- Among children 6–23 months of age: no evidence for associations of agricultural production or income with the anthropometric indices - Among children 24–59 months of age: one log unit increase in agricultural production quantity (kg) and income were associated with 0.020 (p<0.01) and 0.017 (p<0.006) unit increase in Ht/Age Z-score and with 0.2 (p<0.05) and 0.1 (p<0.05) percentage point increase in wasting (Wt/Ht Z-score<-2 SD), respectively
Shack *et al*, 1990 [88]	Papua New Guinea	quantity of crops cultivated (count of plants); income from cash crop sales	household	cross-sectional	Wt/Age, Ht/Age, Wt/Ht, skinfolds, arm circu., Hbg, Htc	56 families (numbers of individuals not given)	≤6	- An increase in income from cash crops by 1 kina/month was associated with an increase of 0.03 points (p<0.01) and 0.02 points (p<0.01) in child Ht/Age and Wt/Age scores, and 0.03 cm (p<0.05) increase in child arm circumference; there was no evidence for statistically significant associations with child Wt/Ht, Hbg, Htc - The quantity of food crop planted was not significantly associated with indicators of child nutritional status

Table 2—6 (*continued*). Summary of studies on the links of crop harvest or yield with child nutritional status and mortality.

Source	Country	Exposure measure	Level of analysis	Study design	Outcome measure	Sample size	Age, years	Key results
Shivley & Sununtnasuk, 2015 [89]	Nepal	crop yield, area of land cultivated	household	cross-sectional	Ht/Age	1,769 children	<5	- Among children ≥2 years: a 1,000 kg/ha increase in crop yield was associated with 0.0457 point increase in Ht/Age Z-score (p<0.05) and a reduction in the risk of stunting by about 2%, no evidence for associations of these measures with farm size - Among children <2 years of age there was no evidence for any of these associations
Stewart *et al*, 1989 [90]	Bangladesh	flood-related crop loss (reported & observed)	household	change in differently affected areas	Wt/Age, Wt/Length, Length/Age, MUAC	281, 264, 268 (differed by survey)	0.5–2.9	- Following a flood in September and its related crop loss, average children's mean % of anthropometric indices from the NCHS median in October, December, and March were as follows: 70.8, 71.3, 72.1 for Wt/Age, 84.9, 85.3, 86.9 for Wt/Length 90.3, 90.3, 90.0 for Length/Age, 131.2, 132.2, 133.6 for MUAC. When monthly anthropometric means were tested using the analysis of variance with age as a covariate, none of the differences in the index values across months were statistically significant (p>0.05)
II. Wider area-level studies on the association of child nutritional status and mortality with spatial variation in crop yield								
Apodaca, 2008 [91]	Developing countries	crop yield, arable land per capita	country	analysis of spatial variation	Ht/Age	137 countries	<5	- 1 unit increase in arable land and yield was associated with 7.75 and 0.14 point reduction in the rate of child stunting, respectively (t<0.10) (*poor reporting of results did not permit interpreting the effect size*)
Block *et al*, 2016 [92]	Nepal	NDVI: year of and prior to birth	NDVI resolution of 5 km	analysis of spatial variation	Ht/Age	5,237 ('06), 2,335 ('11) children	1–5	- Strong evidence for the associations of Ht/Age with NDVI in boys *in utero* – with greatest effect in their second trimester of gestation and in girls – in the first three months after birth. Each 100 point difference in NDVI at those times was associated with a difference in Ht/Age Z-score of 0.088 for boys and 0.054 for girls
Grace *et al*, 2016 [93]	Mali	community land cultivated (over child's lifetime)	community	cross-sectional	Ht/Age	2,830 children	<5	- A unit increase in the % of cultivated area of land in a community was associated with a reduction of about 32% in the odds of being stunted (p=0.05)

Table 2—6 (*continued*). Summary of studies on the links of crop harvest or yield with child nutritional status and mortality.

Source	Country	Exposure measure	Level of analysis	Study design	Outcome measure	Sample size	Age, years	Key results
Johnson & Brown, 2014 [94]	Mali, Burkina Faso, Guinea, Benin	NDVI during the peak crop growing season in the year of birth and 2 years prior to birth	NDVI resolution of 8 km	analysis of spatial variation	mortality, Ht/Age, Wt/Ht, Hbg	838–5,363 children	<3	- NDVI positively associated with child survival and nutrition - NDVI more likely to be positively associated with wasting than stunting Every unit of increase in NDVI was significantly associated with: - reduced odds of death in Burkina Faso by 13% (p=0.015), in Mali by 7% (p=0.036) - 40% increase in stunting in Benin (p=0.033) but 12% decrease in Mali, 2006 (p<0.001) - a reduction in wasting in Mali in 2001 by 11% (p<0.001) and in 2006 by 7% (p=0.016) - an increase in severe anaemia in Mali in 2006 by 16% (p=0.013)
Sedda *et al*, 2015 [95]	West Africa	period (2001–8) mean NDVI	NDVI resolution of 1 km	analysis of correlation and spatial variation	mortality, under-nutrition (*NS*)	*NS*	*NS*	- NDVI was found to be inversely correlated with child mortality (r=−0.66) and undernutrition (r=−0.66)
Shively *et al*, 2012 [96]	Nepal	crop growing season NDVI (stunting: year of birth, wasting: before measurement)	NDVI resolution of 5 km	analysis of spatial variation	Ht/Age, Wt/Ht	5,464 children	<5	- Strong statistical evidence (p<0.01) in support of association of higher NDVI in the year of a child's birth with subsequently higher Ht/Age index values, and of NDVI measured in the year prior to child measurement with subsequently higher Wt/Ht index values (*the manner how the article reported results did not permit interpreting the effect size*)
Shively *et al*, 2015 [97]	Nepal	NDVI anomalies during crop growing season in the year of birth, year prior and after birth	NDVI resolution of 5 km	analysis of spatial variation	Ht/Age, Wt/Ht	2,335 (Wt/Ht), 1,412 (Ht/Age) children	<5: Wt/Ht ≥2: Ht/Age	- Child stunting was correlated with the departure of NDVI from its long-term average during the first year of life, where an increase in NDVI by 1 unit was associated with an increase in stunting (Ht/Age Z-score <-2SD) by <0.1 percentage point (p<0.01) - An increase in NDVI by 1 unit in the month of child measurement was associated with a reduction in wasting (Wt/Ht Z-score<-2 SD) by <0.1 percentage point (p<0.1)
Kinyoki *et al*, 2016a [98]*	Somalia	EVI, rainfall, mean temperature	EVI resolution of 1 km	analysis of spatio-temporal variation	wasting, stunting, under-weight	73,778 children	0.5–5	- Child wasting, stunting and the state of being underweight were significantly associated with the vegetation index (OR 0.66, 95% CrI 0.45, 0.95), (OR 0.59, 95% CrI 0.42, 0.82), (OR 0.69, 95% CrI 0.67, 0.72) and temperature (OR 1.07, 95% CrI 1.03, 1.11), (OR 1.05, 95% CrI 1.01, 1.10), (OR 1.12, 95% CrI 1.07, 1.17), respectively

Table 2—6 (*continued*). Summary of studies on the links of crop harvest or yield with child nutritional status and mortality.

Source	Country	Exposure measure	Level of analysis	Study design	Outcome measure	Sample size	Age, years	Key results
III. Studies of child nutritional status and mortality in relation to temporal (year-to-year) variation in crop yield								
Alba *et al*, 2013 [99]	Tanzania	food security (temporal variation in rice & maize yield)	household	time series analyses	mortality	annual average of 5,129 children	1–5	- Strong evidence for the protective effect of food security in the same month, with an estimated 11.5% decrease in child mortality rates for every 500 kg increase in household food security
Emmelin *et al*, 2008 [100]	Ethiopia	famine, decline in maize yield	HDSS population	descriptive time series	mortality	not given	<5	- Two times higher child (<5 years) mortality rate was observed to coincide with the year of famine, lower maize yields, and failed rains
Hagos *et al*, 2014 [101]	Ethiopia	per capita crop production	administrative district	longitudinal panel study	stunting, wasting, underweight	145 obs. of 43 admin. zones over 1996–2004	<5	- 1 kg increase in per capita crop availability was associated with 0.17 SD increase in the state of being severely underweight (p<0.1) and 0.26 SD increase in severe wasting (p<0.05)

Abbreviations: Arm circu, arm circumference; CI, confidence interval; CrI, credibility interval; Hbg, Haemoglobin; Ht/Age, height-for-age; Htc, Haematocrit; NCHS, National Centre for Health Statistics; NDVI, Normalized Vegetation Index; NS, not specified; OR, Odds Ratio; SD, Standard Deviation; Wt/Age, weight-for-age; Wt/Ht, weight-for-height.

* Variants on these analyses are also reported in several other articles published by the same research group [102–104]

The first set of studies contributed diverse results about cross-sectional associations between proxies of household crop harvest and measures of child nutritional status, suggesting that there is evidence for an association in some settings but not in others. A study in El Salvador suggested an association between the children's height-for-age index with the area of land cultivated by their households [85]. Studies in Zambia and Nepal suggested associations of height-for-age and weight-for-height indices with crop harvest quantity and yield as well as agricultural income among children 2–5 years of age but not among children <2 years [87,89]. By contrast, a study in Northern Laos provided no evidence for the association of the child height-for-age index with household rice harvest [86] and a study in Papua New Guinea found no evidence for the association of child nutritional status with the amount of crops cultivated by households [88]. Two studies addressed the associations of child nutritional status with household-level crop loss, with one study suggesting evidence for the association [84] and the other no evidence [90]. Differences in these findings might reflect some effect of contextual factors and variation of vulnerability across populations. This interpretation, however, is complicated by the diversity of measures these studies used to approximate household crop harvest, which limits their comparability. A further limitation of these studies was their cross-sectional design. What these studies did not elucidate is whether child nutritional status could be related to *year-to-year* changes in crop harvest. This requires analyses based on longitudinal (not cross-sectional) data. Nevertheless, this set of studies suggests that there is some evidence for household crop harvest being a possible determinant of child nutritional status. Correspondingly, these studies may also suggest the pertinence of further examination into the relationship of child nutritional status with yearly harvest changes in these settings.

The second set of studies contributed evidence of the associations of child nutritional status and mortality with spatial variation in proxies of crop yield. An analysis of 137 countries suggested that a country's average crop yield was a statistically significant predictor of national prevalence of child stunting [91]. A study in Mali suggested that there is a positive association between children's height-for-age index with the percentage of the area of land that has been cultivated in their villages over the life-time of each child [93]. A number of studies used the Normalized Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI) (both are measures of the intensity of vegetation cover) as proxies of crop yield. Better child survival and lower risk of wasting were found to be associated with exposure to an increase in these indices *in utero*, early life, and the year of child measurement [94–98,102–104]. Yet, study results differed in relation to the risk of child stunting with some suggesting that greater risk of stunting was associated with an increase in vegetation indices in, or prior to, the year of birth [94,97], while others with their decrease [91,92,94,96,104]. Differences in these results may be related to possible differences in the dominant pathway though which the associations operate in each setting. For example, in some settings increased rainfall, marked by higher NDVI values, may result in flooding, leading to an increased risk of water-borne and water-washed diseases, or it may result in a more favourable environment for disease vectors such as mosquitoes; increased disease risk, in turn, has negative implications for nutritional status [94,97]. In contrast, in other settings higher NDVI values reflect higher crop productivity, which may lead to greater food availability, higher levels of consumption, and improvements in nutritional status [91,92,94,96,104]. Furthermore, vegetation indices may poorly reflect the actual crop yield. Grain formation can be negatively affected even by short spells of adverse weather, especially at critical stages of plant development, without necessarily visibly affecting vegetation, and hence, not being captured in vegetation indices [105]. There are also studies (not included in Table 2–5) that examined the association of child mortality and undernutrition with spatial variation in crop growing season temperature and precipitation [78,106–114]. Yet, their capacity to determine the risks of crop yield variation could still be limited by the lack of clarity over the pathways linking their examined weather parameters with the outcomes (e.g., agriculture and nutrition *vs* vector-/ water- borne disease pathways) [113].

Overall, the second set of studies contributed evidence of more sophisticated questions of the association of child nutritional status and mortality with crop yield variation at specific times of children's lives, e.g., *in utero* and early life. However, these associations were mostly based on spatial, not temporal (*year-to-year*), variation in crop yield. One research group examined the association of child undernutrition (wasting, stunting, being underweight) in relation to the EVI using a spatio-temporal Bayesian model, thus potentially reflecting the effect of both spatial and temporal variation in EVI [98,102–104]. Yet largely, the second set of studies did not determine whether and how child undernutrition and mortality could be related to inter-annual variation in crop yield, such as might arise from adverse weather conditions during the crop growing season. These studies mostly used nutrition and mortality data from Demographic and Health Surveys (DHS) conducted in one or only a few different years, thus, limiting their capacity to establish the effects of *year-to-year* crop yield variation, with further limitations related to the use of vegetation indices instead of actual crop yield data.

The third set of studies contributed evidence of the association of child nutritional status and mortality with temporal variation in crop production [99–101]. I identified only three such studies. One provided a descriptive observation of higher child mortality rates in years of famine marked by a decline in maize yields [100]. Another study was based on longitudinal analyses of panel data defined at the level of administrative districts in Ethiopia [101]. It suggested that there is weak evidence for the association of increased severe wasting and being underweight with an increase in per capita crop availability, as well as evidence for positive associations of stunting and being underweight with increased extreme forms of rainfall but generally negative associations with higher growing season temperatures. The authors suggested that the counter-intuitive direction of the association of increased severe wasting and being underweight with an increase in per capita crop availability, here could be explained by the implementation of public health measures and support in response to crop deficits [101]. However, the quality of this analysis was constrained by the use of aggregated data at the level of administrative zones and the resulting small sample size (145 observations of 43 administrative zones over time). The third study was based on time series analyses of child mortality in relation to a measure of household food security (monthly proxy of kg of rice and maize harvest available to a household) over the period of 1997–2009 [99]. The study demonstrated strong evidence for the association of the food security measure with child mortality in the same month, estimating an 11.5% decrease in the child mortality rate for every 500 kg increase in the measure of household food security. This analysis was controlled for time trend, season, and monthly rainfall, thus, limiting possible confounding by variations in rainfall and vector- or water-borne diseases. In my view, this was the only study which provided quality evidence concerning the risk of temporal crop yield variation for child mortality, such as might arise from adverse weather conditions during the crop growing season.

2.4. Implications for thesis research

The preceding section provided a critical summary of studies on the links between crop yield or harvest and child undernutrition and/or mortality in low-income settings. It suggested specific gaps in the empirical evidence that is required to substantiate the proposed climate change impact on child undernutrition through reductions in crop production.

Firstly, there was limited evidence for the vulnerability of children's nutrition to low crop harvest in their households. The studies on the association of child nutritional status with household crop harvest suggested that such vulnerability might be present in some but not all settings. Similarly, the magnitude of such vulnerability (where present) appears to vary across areas and households. Yet evidence for differences in the vulnerability of child nutrition in relation to low household crop harvest is inconclusive, requiring further studies at the household level.

Secondly, there was limited evidence for associations of *year-to-year* variation in crop yield with child undernutrition and mortality. I was particularly interested in studies examining annual variation in crop yield or harvest, as impacts of such variation can potentially be related to changes in weather variability and climate change. I identified only one study as providing high quality evidence of the risk posed by unexceptional (i.e., without extreme variations from the annual average) *year-to-year* variation in crop yields. Other studies did not give evidence of the risks of annual crop yield variation largely due to designs based on cross-sectional data and spatial, as opposed to temporal (*year-to-year*), variation in yield. Their capacity to provide information about the risks posed by crop yield variation was often further limited by their use of indirect, and potentially inaccurate, proxies of crop growing conditions, such as vegetation indices, instead of the actual crop yield measurements.

The critical summary of literature provided in this chapter suggests specific requirements for further empirical evidence. Overall, there appears to be a need for further research on *year-to-year* variation in crop yield as a risk factor for child undernutrition and mortality in the context of weather variability in subsistence farming populations. This would require, firstly, further household-level studies to examine and account for possible differences in the vulnerability of child nutrition to low harvest levels. Secondly, this would require empirical analyses of the associations of child nutritional status and mortality with *year-to-year* variation in measures of actual crop yield, reflecting such variations as might arise from agriculturally unfavourable weather. The need for research on unexceptional crop yield variation was further highlighted by the meta-analyses [76,77] which suggested that moderate levels of food insecurity may pose more adverse health effects than high food insecurity levels.

Based on these research needs, in the next chapter I formulate specific objectives for this thesis and provide background to the study setting.

Chapter 3: Thesis aim, objectives, and study setting

The previous chapter suggested specific gaps in the evidence that is required to substantiate the proposed climate change impact on child undernutrition through reductions in crop production in subsistence farming populations. This chapter presents the aim and objectives of this thesis, which I formulated in response to these gaps. Here I also introduce the study setting.

3.1. Thesis aim and objectives

The overall aim of this thesis is to examine crop yield variation as a risk factor for child undernutrition and mortality in a subsistence farming population in the context of weather variability. The aim is addressed through the following three objectives:

1. To examine the relationship between children's nutritional status, measured by middle-upper arm circumference (MUAC), and *household* cereal crop harvest;
2. To examine associations between child survival over first five years of life, nutritional status, measured by MUAC, and *inter-annual* food crop yield variation;
3. To quantify the impact of low crop yields on child mortality and to attribute such impacts to unfavourable growing-season weather conditions, as observed in the recent past and projected under a future climate change trajectory.

The first and second objectives have been set to examine *whether* variation in crop yield could be a risk factor for child undernutrition and mortality in this setting. The third quantifies *how much* child mortality can be attributed to annual crop yield reductions and the possible impact of a future climate change trajectory on this attributed burden.

The thesis objectives directly map onto the conceptual impact pathway of crop yield variation as a risk factor for child undernutrition and mortality among subsistence farmers in the context of weather variability (Figure 3–1). The first and second objectives are set to contribute evidence of the statistical associations "crop production – child undernutrition", "crop production – child mortality", and "child undernutrition – child mortality". The third objective draws on evidence for the association between "crop production – child mortality" and a statistical weather-crop model (co-developed with my research collaborators) that informs the association "weather variability – crop production" to estimate the burden of child mortality attributable to low crop yields under the current and future weather variability.

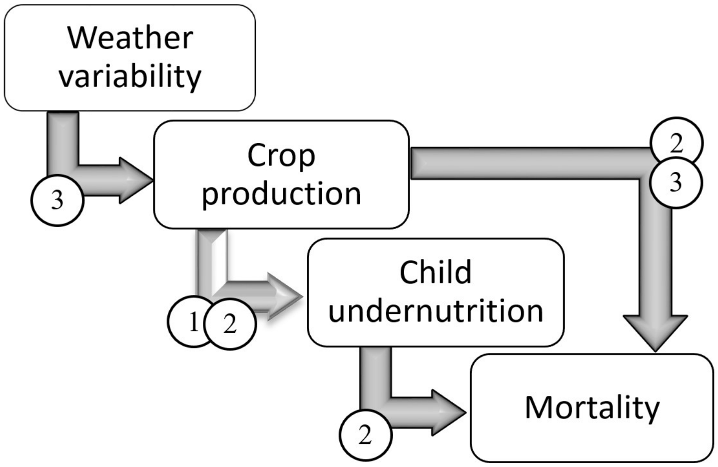


Figure 3—1. Conceptual impact pathway addressed in this thesis.

Numbers on the arrows indicate the number of the thesis objective that examines the link corresponding to the arrow.

Thus, the research programme of this thesis is designed to contribute empirical epidemiological evidence of the key associations characterizing crop yield variation as a risk factor for two outcomes – child undernutrition and mortality, and to provide estimates of the possible magnitude of the burden of child mortality attributed to this risk factor under the current and future weather variability. Table 3–1 provides a summary of how thesis chapters and papers correspond to the thesis objectives.

Table 3—1. Summary of how thesis chapters and papers correspond to the objectives.

Thesis objective	Thesis chapter	Research paper	Journal	Publication status
n/a	2	1) Drought Exposure as a Risk Factor for Child Undernutrition in Low- and Middle-Income Countries: A Systematic Review and Assessment of Empirical Evidence	Environment International	Prepared for submission
1	4	2) Household Crop Harvest and Children's Nutritional Status in Rural Burkina Faso	Environmental Health	Published
2	5	3) Annual Crop Yield Variation, Child Survival and Nutrition among Subsistence Farmers in Burkina Faso	American Journal of Epidemiology	Published
3	6	4) Mortality Impact of Low Crop Yield in Rural Burkina Faso in the Context of Current and Future Climates	Lancet Planetary Health	Submitted

3.2. Study setting and data

To address the thesis objectives, I decided to undertake a series of studies/analyses examining a subsistence farming population in rural Burkina Faso. I selected this setting for three main reasons: (1) the likely vulnerability of the local population to crop yield variation, (2) the past variation in crop yield and its sensitivity to weather variation, and (3) the availability of high quality data which permitted me to address thesis objectives.

Burkina Faso

Burkina Faso is a landlocked country in western sub-Saharan Africa (Figure 3–2). In 2008, it was recognized to be off the track in terms of progress towards the 1st MDG ("Eradicate extreme poverty & hunger"). In that year Burkina Faso was estimated globally to have the 14th highest child mortality rate <5 years (169 deaths per thousand live births) and the total prevalence of moderate and severe stunting among children <5 years reaching 36% (a high prevalence according to the WHO classification [115], but lower than in such countries as India, Pakistan, Nepal, Rwanda, and Guinea-Bissau) [116,117]. The national prevalence of severe and moderate wasting among children <5 years was 11% in the year 2012 [116]. It is one of the world's poorest countries with nearly half of the population living below the poverty line of US$1.25 income per day [118].

Agriculture is the country's main economic sector with nearly 80% of the economically active population employed in this sector, mostly as subsistence farmers (Figure 3–3) [119]. Burkinabe mainly rely on rain-fed agriculture, leading to their high vulnerability to unfavourable changes in weather patterns, with droughts recognized as the top natural disaster in the country [37,120]. Crop yield in Burkina Faso is highly dependent upon variation in such weather patterns as the start and length of the rainy season, intra-seasonal rainfall distribution, and changes in the diurnal temperature range [121]. Global warming of 2 ºC above the pre-industrial levels in Burkina Faso is estimated to translate into an average loss of 10–20% in grain yield [121].

On average, cereals constitute 72% of daily kilocalorie (kcal) consumption in Burkina Faso, with other food groups contributing much smaller proportions: vegetables 0.44%, meat 3.18%, and fish 3.45% [122]. Hence, local food energy intake is

Figure 3—2. Map of Burkina Faso, indicating location of the Nouna HDSS.

Figure 3—3. Photos from the study setting.

Top left – crop field in the dry season, top right and middle & bottom left – women processing the harvested grain, bottom right – children having a millet porridge meal from their common pot.

Photos taken in Nouna HDSS area, Kossi province, Burkina Faso in March 2015 by Kristine Belesova.

likely to be highly sensitive to variation in crop yields and changing variation in weather parameters with climate change.

Nouna HDSS

I examined a rural population in Kossi province of western Burkina Faso (Figure 3–2), which has been surveyed by the Centre de Recherche en Santé de Nouna (CRSN) as a part of the Nouna Health and Demographic Surveillance System (HDSS) since 1992. The CRSN hosted me in Nouna, Burkina Faso for a three-month long field visit which allowed me to identify, acquire, compile, link, and verify each data set collected by the Nouna HDSS that was of relevance to this research. During the visit I gained a detailed understanding of the data collection process and developed an in-depth understanding of the local context through informal observation and discussions with local researchers, officials at the relevant government agencies, and the local community.

The Nouna HDSS was developed as part of a collaborative research and health policy project of the Ministry of Health of Burkina Faso and the University of Heidelberg called PRAPASS (Projet de Recherche-Action pour l'Amélioration des Soins de Santé) [123]. The CRSN was established in 1999 to institutionalise the project. It was directly linked to the Secretary General of the Ministry of Health of Burkina Faso and received substantial allocation of infrastructural and human resources [123]. Hence, the CRSN serves as a platform for interdisciplinary research in epidemiology, public health, parasitology, entomology, and health economics, which administers the Nouna HDSS [123].

The HDSS was initially designed as a survey of the population of all villages (n=39) that fell into the former catchment area of three local health care facilities [123]. The first census of this population was conducted in 1992 and supplemented with a registration of vital events – births, deaths and migration [123]. It was updated through subsequent censuses in 1993 and 1998. In 2000, the study population was extended to 41 villages, which fell into the re-organized catchment area of four local health care facilities, and the semi-urban Nouna town [123]. The HDSS population was further expanded in the year 2004 to incorporate additional 17 villages [124]. Village population in 2007 ranged from 78 to 3,199 people (mean: 944; median: 735) [124]. In the year 2010 the HDSS population reached 89 thousand people [77], covering 58 villages and a semi-rural Nouna town (Figure 3–4). Many staff members at the CRSN have been trained in postgraduate training programmes at the University of

Heidelberg, University of Montreal, University of Witwatersrand, Université de Paris XII, and University of Ouagadougou [124].

Figure 3—4. Map of the Nouna HDSS villages and the semi-rural Nouna town (Image: Diboulo *et al* [161], reproduced under the CC BY-NC 3.0 license).

The Nouna HDSS has been part of the International Network for the Demographic Evaluation of Populations and Their Health (INDEPTH). The INDEPTH network is an umbrella organization of 43 HDSS sites (as of 2014) in low-and middle-income countries in Africa, Asia, and Oceania providing population-based data on health, which is scarce in these regions due to the absence of reliable routine reporting [125]. At the establishment of an HDSS a baseline census is conducted on the selected population, assigning each household and individual a unique identification number [125]. The population is tracked as an open dynamic cohort through 3–4 annual household survey visits, which update records on births, migrations, and deaths (Figure 3–5) [125].

In the Nouna HDSS, the visits were performed every three months until the year 2006 and every four months thereafter by trained field staff [124]. Here, the data collection process is also supported by one key informant per village, who is a resident of the village and is trained in recording vital events on a daily basis, thus, further ensuring data accuracy [124]. Data is collected on the date of birth, death, in- or out-migration, religion, ethnic group, household characteristics, and family links between household members (e.g., parent identification number) [124]. Quality control procedures in the Nouna HDSS include: (1) re-interviewing a random sample of 5–10% of the households by a supervisor, (2) data entry routines that include logical and consistency checks of basic variables, and (3) systematic checking among the data entry clerks [126].

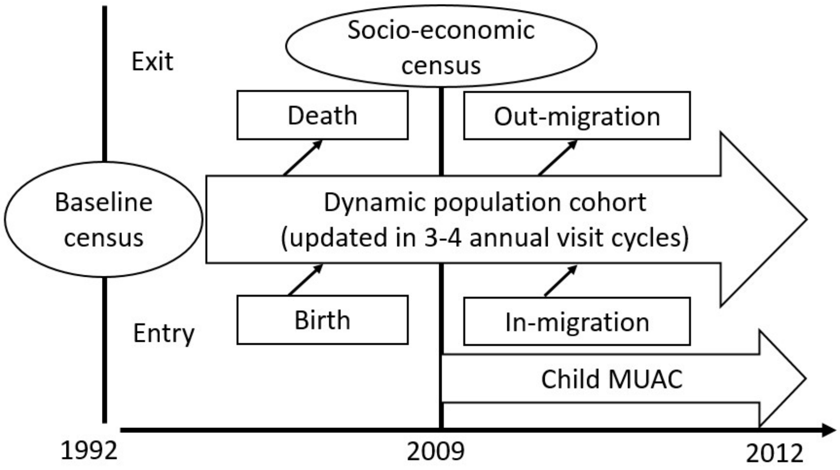


Figure 3—5. Conceptual structure of the dynamic cohort model of the Nouna HDSS site and the additional data that were used in this thesis (Image: adapted from Sankoh & Byass [125]**, reproduced under the CC BY-NC 3.0 license).**

In addition to the baseline census, in the Nouna HDSS a socio-economic population census was conducted in the year 2009, which included a questionnaire on self-reported household crop harvest in this year and child MUAC measurements (Figure 3–6). Since its inception, a number of epidemiological and clinical studies have been nested into the Nouna HDSS dynamic cohort, providing potential access to data on additional health parameters of the population [7]. With one such study focusing on optimizing the impact and cost-effectiveness of child health interventions (OPTIMUNIZE) [127], child MUAC data collection has been gradually incorporated into the Nouna HDSS survey rounds since the year 2009. All MUAC measurements were performed by trained field staff using MUAC measuring tapes. Until the year 2012, MUAC data collection was linked to an immunisation programme, and hence, the MUAC of each child was measured only once – at the time of the immunisation.

From 2012 onwards, MUAC measurements were performed with each HDSS survey round, hence, producing data on several MUAC measurements per child. The MUAC data has not been cleaned at the CRSN when I received it. Therefore, all the cleaning of the MUAC database I completed myself. This included internal variable consistency checks, consistency and logical checks across variables, analyses and exclusion of duplicate entries.

The HDSS core data on vital events, socio-economic data from the census of the year 2009 (including household crop harvest data), and MUAC data permitted the analyses required to address the thesis objectives. Additional data (on agricultural production and weather) used in this thesis are summarized in Figure 3–6 and described in those chapters detailing the corresponding analyses.

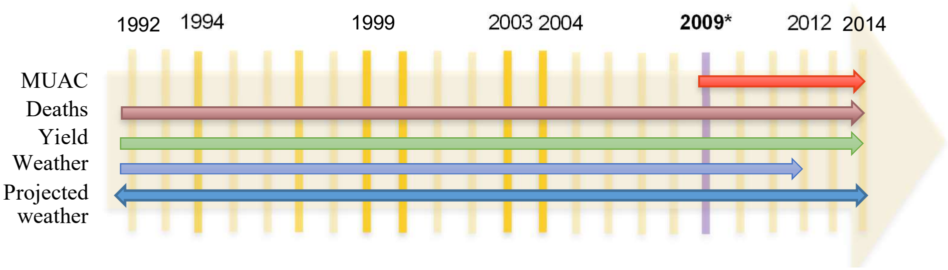


Figure 3—6. Diagram indicating time-spans of the availability of data used for analyses in this thesis.

*2009 was the year of the Nouna socio-economic census, providing data on household crop harvest and many household characteristics

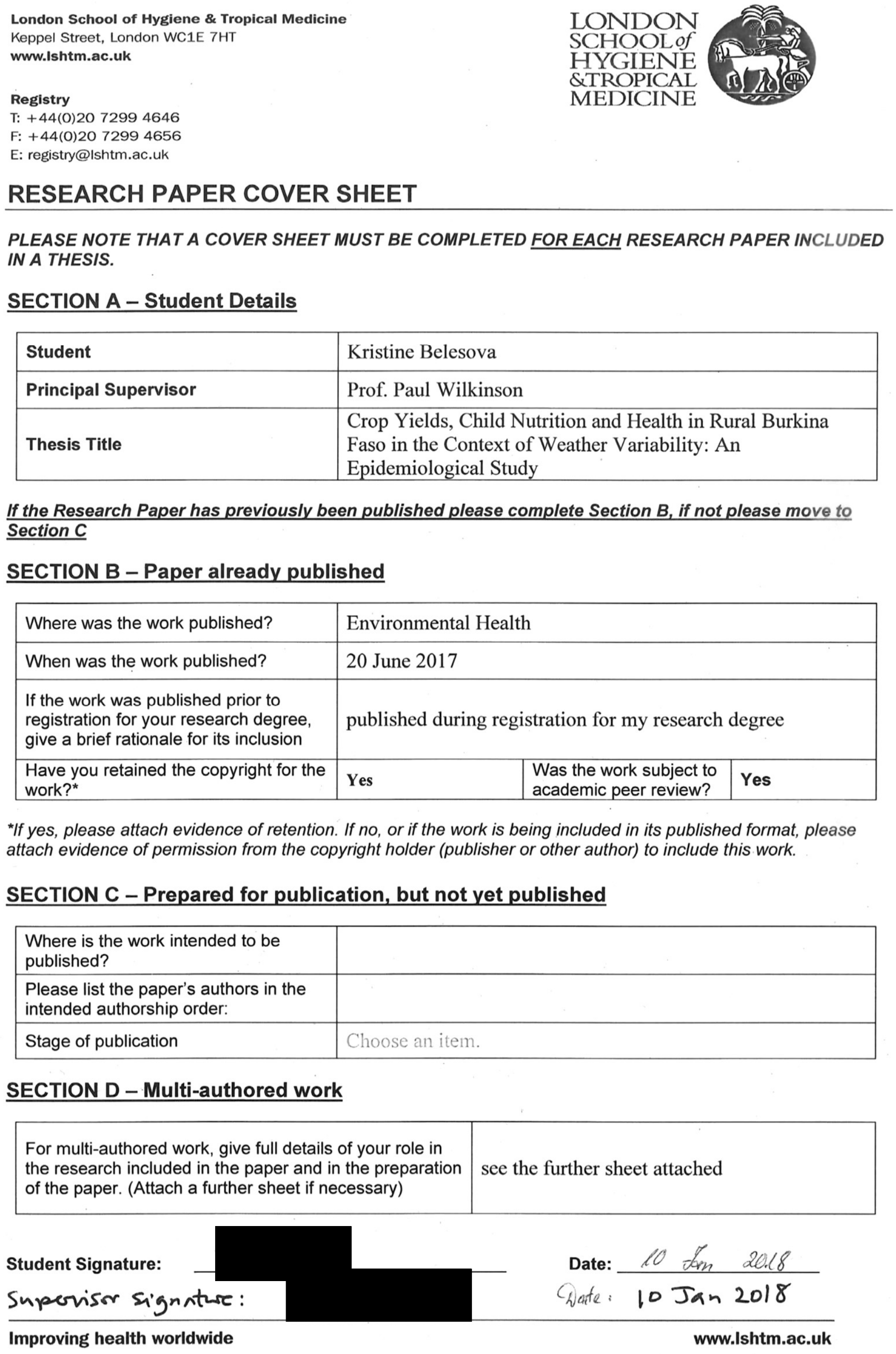
3.3. Ethics approval

The study was conducted following the ethical standards of the Declaration of Helsinki [128]. It was approved by the London School of Hygiene and Tropical Medicine Observational Ethics Committee (No. 8624) and Comité Institutionnel d'Ethique du Centre de Recherche en Santé de Nouna (No. 2015-04-/CIE/CRSN) (Annex 1 and 2).

Chapter 4: Household crop harvest and children's nutritional status

This chapter assesses the relationship between the food energy value of household crop harvest and children's MUAC in the Nouna HDSS population. This assessment aims to address the first objective of this thesis, namely to examine the relationship between children's nutritional status and cereal crop production. The analysis was performed cross-sectionally in a year of average agricultural productivity. Its results provide evidence concerning the degree to which children's nutritional status is sensitive to low household crop harvest in a year with average yield in this area, as observed over the past 30 years.

4.1. Paper 2 *Household harvest and child MUAC*



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SECTION A – Student Details

Student	Kristine Belesova
Principal Supervisor	Prof. Paul Wilkinson
Thesis Title	Crop Yields, Child Nutrition and Health in Rural Burkina Faso in the Context of Weather Variability: An Epidemiological Study

If the Research Paper has previously been published please complete Section B, if not please move to Section C

SECTION B – Paper already published

Where was the work published?	Environmental Health		
When was the work published?	20 June 2017		
If the work was published prior to registration for your research degree, give a brief rationale for its inclusion	published during registration for my research degree		
Have you retained the copyright for the work?*	**Yes**	Was the work subject to academic peer review?	**Yes**

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SECTION C – Prepared for publication, but not yet published

Where is the work intended to be published?	
Please list the paper's authors in the intended authorship order:	
Stage of publication	Choose an item.

SECTION D – Multi-authored work

For multi-authored work, give full details of your role in the research included in the paper and in the preparation of the paper. (Attach a further sheet if necessary)	see the further sheet attached

Student Signature: [redacted] **Date:** 10 Jan 2018

Supervisor signature: [redacted] Date: 10 Jan 2018

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Section D – Multi-authored work

I conceived the idea and designed the study with advisory input from my thesis supervisor Prof. Paul Wilkinson and advisors Dr. Antonio Gasparrini (on statistical analyses) and Prof. Rainer Sauerborn (on local context). I identified, cleaned, and linked the databases, and performed all analyses independently. I prepared the first draft of the manuscript, further editing it in response to co-author's comments, and responding to all comments from the reviewers and editors until the publication of the article in the journal *Environmental Health*.

Student signature: Belesova 10 Jan 2018

Supervisor signature: PWilkin 10 Jan 2018

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http://doi.org/10.1186/s12940-017-0258-9

Changes made to this manuscript post-publication include minor grammar and style corrections, change to the numbering of tables and figures for the formatting purposes of the thesis, and the following improvements suggested by the thesis examiners:

- Addition of details on the study sample
- Technical details on the construction of the index of village infrastructural development index
- More selective presentation of mean *vs* median statistics in Table 4–1
- Addition of Table 4–2 and supplemental Figure 4–4
- Addition of the results of significance tests in Supplemental Table 4–7

Paper 2:

Household Cereal Crop Harvest and Children's Nutritional Status in Rural Burkina Faso

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Short title: Household crop harvest and children's nutritional status

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Abstract

Background

The reduction of child undernutrition is one of the Sustainable Development Goals for 2030. Achievement of this goal may be made more difficult in some settings by climate change through adverse impacts on agricultural productivity. However, there is only limited quantitative evidence of the link between household crop harvests and child nutrition. We examined this link in a largely subsistence farming population in rural Burkina Faso.

Methods

Data on the middle-upper arm circumference (MUAC) of 975 children ≤5 years of age, household crop yields, and other parameters were obtained from the Nouna Health and Demographic Surveillance System. Multilevel modelling was used to assess the relationship between MUAC and household crop harvest in the year 2009, estimated in terms of kilocalories per adult equivalent per day (kcal/ae/d).

Results

14% of children had a MUAC <125 mm (a value indicative of acute undernutrition). The relationship between MUAC and annual household food energy production adjusted for age, sex, month of MUAC measurement, household wealth, whether a household member had a non-agricultural occupation, garden produce, village infrastructure and market presence, suggested a decline in MUAC occurred below around 3,000 kcal/ae/d. The mean MUAC was 2.49 (95% CI 0.45, 4.52) mm less at 1,000 than at 3,000 kcal/ae/d.

Conclusions

Low per capita household crop production is associated with poorer nutritional status of children in a rural subsistence farming population in Burkina Faso. This and similar populations may thus be vulnerable to the adverse effects of weather on agricultural harvest, especially in the context of climate change.

Keywords: climate change, malnutrition, undernutrition, MUAC, agriculture, crops, food security, children's health, environmental epidemiology

Background

Reducing child undernutrition and hunger is at the top of the global development agenda. It is the primary objective of Sustainable Development Goal (SDG) No. 2 (Target 2: "by 2030 end all forms of malnutrition, including achieving by 2025 the internationally agreed targets on stunting and wasting in children under five years of age [..]" [1]) and is reflected in the policy agendas of many development agencies [2]. Malnutrition is estimated to be responsible for over a fifth of the global disease burden in children under five years of age [3,4] and for 45% of the 5.9 million deaths in children under five in 2015 [5]. Legacy effects of childhood undernutrition may also continue into adulthood. Adults undernourished in childhood are more susceptible to infectious [6] and chronic disease [7], have lower economic productivity [8], and are more likely to have compromised cognitive development [9].

While the proportion of undernourished children in developing regions dropped from 23.3% in 1990–1992 to 12.9% in 2014–2016, the rate of improvement over time has been slowing [10]. Climate change impacts on agricultural productivity may further challenge the achievement of SDG 2. Some analyses suggest that, in some settings, it could even lead to the reversal of the recent trend of decreasing undernutrition [11–16].

Household food security, a key determinant of children's nutritional status [4], is widely recognised to have four key dimensions: food availability (sufficient quantity of food of adequate quality), food access (adequate resources to acquire appropriate foods), utilization (sufficient nutrient and energy intake, resulting from appropriate food preparation, diet, intra-household food distribution, feeding practices, good care), and stability (access to adequate food at all times) [17,18]. In subsistence farming populations the agricultural harvest is both a source of food and of income for food purchases [19], yet its yield may vary appreciably because of variations in weather and other factors. Such populations therefore face potential vulnerability in relation to at least three of the four pillars of food security: food availability, access, and stability.

What is unclear, however, is the degree to which reduced household crop yields result in compromised nutrition. Studies in different settings provide differing results on the association between children's nutritional status and household food crop production [20–24], possibly reflecting the effect of context-specific factors and variation in vulnerability across study populations (e.g., previously suggested to differ by the level of income [25–27], diversity of the cultivated crops [28,29], gender [30], and age [24,31]).

In this paper we report a study examining the relationship between children's nutritional status, measured by middle-upper arm circumference (MUAC), and household cereal crop production in a largely subsistence farming population of rural Burkina Faso.

Methods

Study area and population

Burkina Faso is a land-locked low-income country in West Africa, which in 2009 was ranked 6th from the bottom in terms of the Human Development Index [32]. In 2009 46.7% of the population lived below the poverty line of 1.25 USD per person per day. 73.5% of the population is rural and relies on rain-fed agriculture [33].

The study was conducted within the population of the Nouna Health and Demographic Surveillance System (HDSS) in Kossi province of Western Burkina Faso (Figure 4–1), which has been surveyed by the Centre de Recherche en Santé de Nouna (CRSN) since 1992. The Kossi province is classified as a dry orchard savannah, and receives on average 685 mm of rainfall per year [34,35]. The single agricultural production season lasts during the rainy season starting in June and ending in October [35]. Agricultural productivity in the Kossi province in the year of study (2009/10) was close to the average for the past 30 years. Cereals constitute 72.2% of the average daily kilocalorie (kcal) consumption in the country as a whole [36], while other food groups contribute much smaller proportions: vegetables 0.44%, meat 3.18%, and fish 3.45% [36].

The Nouna HDSS population almost exclusively relies on rain-fed crop produce [34,35,37]. Ninety-eight per cent of the population cultivate crops for food, and in most cases at levels no greater than required to meet household needs. The main food crops cultivated are millet, sorghum, fonio, maize, and rice. Farmers also grow cotton, sesame, and peanuts. Although here these three are referred to as cash crops, they are mostly grown to meet day-to-day household expenses (e.g., health care and schooling fees) from small scale sales. Sesame and peanuts can also serve as food for the household.

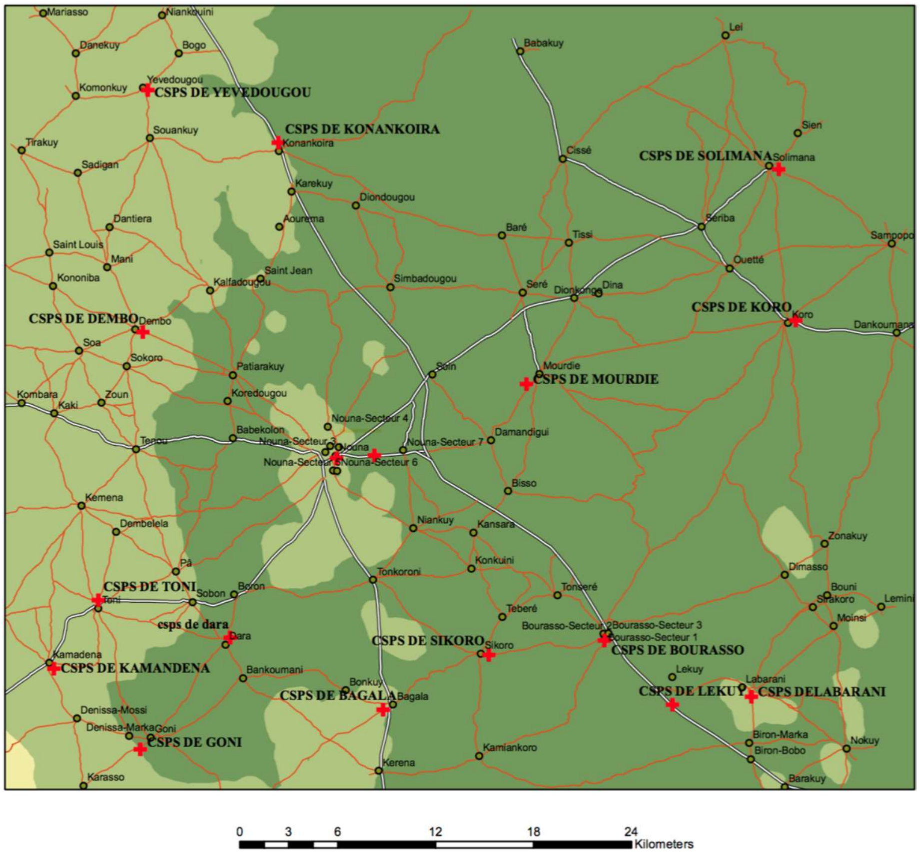

Figure 4—1. Map of Nouna HDSS villages.

Here we follow the Nouna HDSS definition of a household as a socio-economic unit whose members are usually, but not necessarily, related by family ties; household members live together, share resources, and jointly meet their food and other vital needs under the authority of a single person, referred to as the head of household [38]. The head of household oversees agricultural activities undertaken by household members in the crop fields. Crop cultivation and harvest are mostly performed by men. In some households women may participate in selected stages of agricultural work, such as sowing and weeding. Women frequently maintain gardens where they cultivate vegetables, fruit, and herbs. Women are also responsible for grain processing, food preparation, and sales of their garden produce and food products.

Previous studies indicate high levels of child undernutrition in the Nouna HDSS population. In a sample of 460 children 6–31 months of age taken in June 2009 35%

were underweight (weight-for-age Z-score< -2 standard deviations (SD)), 30% stunted (length-for-age Z-score < -2 SD), and 26% had wasting (weight-for-length Z-score < -2 SD) [39]. The mean MUAC in this sample was 140 mm with the standard deviation of 12 mm [39].

Study sample

The study was of children aged 0–5 years who had undergone routine measurement of MUAC as part of the HDSS survey protocol in the year 2010. Such measurements were made in 604 households (5.83% of all 10,364 households in the Nouna HDSS population). Of these, we selected for our analysis the 545 households (containing 975 children ≤5 years in 52 villages in the Nouna HDSS area and Nouna town; the number of study subjects per village ranged from 1 to 172 (mean: 19, median: 12)), excluding those households that were not involved in food and/or cash crop production. Although these households were not selected by random sampling of all children in the HDSS (but rather on the sample of children who had had MUAC measurements in the year 2010 which were made during the immunisation of all children<5 years of age not already immunised in the preceding years), inclusion of households in the MUAC measurement survey was non-selective with regard to household characteristics, and the children ≤5 years in our sample have similar demographic and socio-economic characteristics to those of children ≤5 years in the wider population, except with regard to age (see Supplementary Table 4–4 at the end of this chapter). The MUAC measurement protocol specifically targeted infants <6 months, who are therefore substantially over-represented in the sample (it must be noted that MUAC measurements in the age group of 0–6 months are generally not considered comparable to those of children 6 months–5 years of age, as MUAC is notably more age-depended in the former than latter age group).

Data

The data assembled for our analyses were as follows:

(1) Middle upper arm circumference (MUAC) – the main outcome variable

We used the MUAC measurements collected by the CRSN survey team between March and August 2010. MUAC values greater than 5 standard deviations of the mean (i.e., outside the range 67 to 218 mm) were considered implausible and excluded from analysis [40–42]. MUAC is a commonly used anthropometric measure indicative of children's short-term nutritional status and shown to be highly correlated with weight change [43]. In the age group of 6 months–5 years MUAC values <125 mm are commonly interpreted as indicative of moderate acute undernutrition and values <115 mm of severe acute undernutrition [44–47]. These cut-off values do not apply to children <6 months of age [44–47].

(2) Food energy value of the household cereal crop harvest in 2009 – the explanatory factor of primary interest

Data on the annual quantity of each food and cash crop harvested by a household in 2009 (i.e., in the year before MUAC measurements) were recorded in the HDSS socio-economic census survey. Quantities described in such terms as tin, can or charrette were converted into kilograms using conversion factors provided by the CRSN. From these we computed two measures:

The energy value of average daily household *food cereal* crop produce in kilocalories/adult equivalent/day (kcal/ae/d), E_f

$= \sum_i (h_i \times c_i)/\text{ae}/356.25$

The energy value of average daily household *food and cash* crops combined (kcal/ae/d), E_{fc}

$= (\sum_i (h_i \times c_i) + c_{millet} \times \sum_j (h_j \times p_j)/p_{millet})/\text{ae}/356.25$

where

i – food cereal crop: millet, maize, sorghum, fonio, rice

j – cash crop: cotton, peanuts, sesame

h – weight (kg) of the crop

c – caloric value of 1 kg of the food crop i [48]

p – market price of 1 kg of peanuts, sesame, or millet in December 2009 in Nouna market prices or 1 kg of cotton in SOFITEX [51,52]

ae – number of adult equivalents (ae) in the household, using weights to reflect differences in physiological food energy needs by age and sex (a 30–60 years old male was given the weight of 1) [49,50]

Thus, our main measure of food availability, E_f, was based on the cereal crop harvest and does not consider the usually modest but unquantified food energy from garden produce (vegetables, fruit, herbs etc.). (Possible differences related to the availability of garden produce were captured by adjusting for the presence of the garden produce as a binary measure in analysis – see below).

The E_{fc} indicates the maximum potential food energy that households could acquire using all income from cash crops to purchase millet (if they chose to do so) and consuming all of their food crop harvest. I did not translate the energy value of cash crops themselves, (although edible cash crops are occasionally used by households to produce condiments, these are mainly produced for local sales; cash crops also include non-edible produce such as cotton) but for analysis used the energy equivalent of the cash they might generate if spent on millet (the most popular food crop in local diets).

The value of ae was calculated following the method suggested by Smith and Subandoro [50], where age and sex-specific energy requirements of all household members are standardised against the energy requirements of a 30–60 years old male, but using the latest guidelines on energy and protein requirements [49,50], and assuming moderate activity levels for household members.

The kcal value of cash crop produce was estimated as the amount that would be available if the household sold all their cash crop harvest (cotton to SOFITEX in 2009, peanuts and sesame on the Nouna market in December 2009) and used the entire income from these sales to purchase millet on the Nouna market in December 2009. Data on the price of millet, sesame, and peanuts were collected by CRSN from the Nouna town market in December 2009, and that of cotton from the cotton producer's price reports for 2009/10 provided by the Societé Burkinabé des Fibres et Textiles (SOFITEX), the biggest cotton company in Burkina Faso controlling cotton production in the Kossi province [51,52].

(3) Individual, household, and village-level co-variates

Data on child's age, sex, and month of MUAC measurement, as well as household characteristics (number of people in the household, age categories of household members, household members' occupations, housing condition and assets) were obtained from the HDSS surveys.

As a measure of socio-economic status, we used the household wealth index of Schoeps et al. (2014), re-coded into quartiles. The wealth index reflects household asset ownership (e.g., means of transport, agricultural assets, household items, such as radio, television, refrigerator, modern stove etc.) and housing conditions (e.g., habitation type, type of roof and walls, source of lighting, type of toilet and sanitation, water source in the dry and rainy season, energy source for cooking) [53]. The choice of quartiles rather than quintiles was largely arbitrary (both are common choices) but we chose quartiles to reduce small numbers in individual strata.

We used a binary variable indicating if there is any member in the household who has a non-agricultural occupation to adjust for any differences in the association of food energy from crop production and children's MUAC related to income from other employment.

We used an indicator of whether a household had any garden produce, i.e., vegetables, fruits, and herbs, to adjust for food energy and nutrients households produced in addition to their cereal crop harvest or additional income that could have been generated from garden produce sales.

Data on village characteristics (presence of health care, education, and administrative facilities, markets, as well as the quality of roads and water wells) were obtained from the geographical information system database of the CSRN. From these we constructed a variable indicating the level of village infrastructure development, using principal components analysis of the variables just listed. The variable was constructed from the first principal component, which explained 50% of the variance (second and third components explained 20% and 12% correspondingly with fourth to eight components explaining <10%), recoded into quartiles. Verbal informed consent was obtained by CRSN at the time of data collection in agreement with the local community and with the approval of the Observational Ethics Committee and the Comité Institutionnel d'Ethique du Centre de Recherche en Santé de Nouna. Our study was also approved by the London School of Hygiene and Tropical Medicine Observational Ethics Committee.

Analyses

The main analyses were made of MUAC as a continuous measure, but for descriptive statistics MUAC was also classified using the cut off values of 125 and 115 mm indicative of moderate acute and severe acute undernutrition [45].

The association of children's nutritional status (MUAC) with the two measures of household crop harvest (E_f, and E_{fc}) was examined using multilevel regression models, accounting for clustering at the village level. Additionally, we examined interaction of these associations with the children's sex.

We used two methods of model-fitting: (i) restricted natural cubic splines (one internal knot placed at the median value of the E_f or E_{fc} [54]) to show variation in MUAC as a smooth function of E_f or E_{fc} and (ii) a piecewise linear regression model with a single change point below which MUAC was assumed to have a linear relationship with E_f or E_{fc}, zero gradient was assumed above the change point. The latter models were fitted to be able to represent the relationship between MUAC and E_f or E_{fc} as a single regression slope. Akaike Information Criterion (AIC) and Likelihood Ratio (LR) tests were used to assess model fit including the number of knots for the restricted natural cubic spline models.

For the piecewise linear regression models, we specified the change point *a priori* at 2,900 kcal/ae/d, which corresponds to the recommended energy intake for a moderately active adult. For consistency, we used the same change points for piecewise models where E_f and E_{fc} were specified as the exposure.

All regression models were adjusted for potential confounders [55], namely: age, sex, month of MUAC measurement, the household wealth index, a village-level indicator of infrastructure development, and binary indicators of: participation of any household member in a non-agricultural occupation, whether the household had any garden produce, and a village-level indicator of the presence of a market. We also included an indicator of whether any of the crop types cultivated by the households in the year of study failed to provide any harvest to see if model results were sensitive to this adjustment. For transparency, we present the model results after having added selected groups of a priori selected confounders (grouped as individual level confounders and as household and village level confounders) until the full model with all confounders included.

Sensitivity analyses were undertaken to assess the impact of the exclusion of observations from households with high crop production values (>8,000 kcal/ae/d from food crop harvest and >15,000 kcal/ae/d from food and cash crop harvest combined) – see supplementary material (at the end of this chapter). Statistical analyses were carried out in Stata 14.1 [56].

Results

Characteristics of the study population are given in Table 4–1. Nearly 50% of children in our analyses were <6 months of age because of the survey methods which targeted such children (as the survey was based on a sample of children who had had MUAC measurements in the year 2010 which were made during the immunisation of all children <5 years of age not already immunised in the preceding years, i.e., children born after, or were missed in, the preceding round of the immunisation). The mean household size was 11 people. 31% of the households had at least one member involved in a non-agricultural occupation (such as pottery, brick making, trade, or other income-generating activity).

Villages varied in the level of their infrastructural development assessed by the presence/absence of administrative, educational and medical facilities, market, transport, and water infrastructure. A market was present in only 37% of them.

Most of the crop produce in the year 2009 was derived from millet and sorghum (Table 4–1; Figure 4–2). The harvest size varied considerably across households and crop types (Figure 4–2). 70% of the households produced garden produce, such as vegetables, fruit, and herbs (Table 4–1).

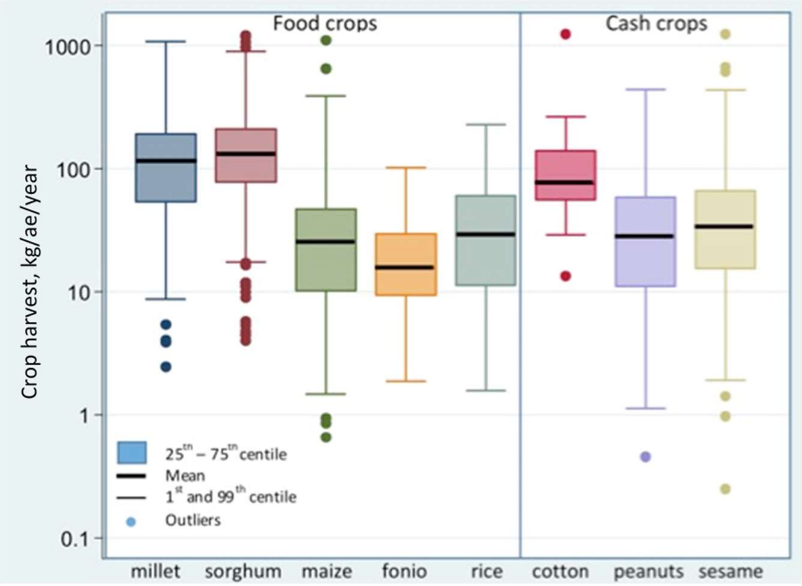

Figure 4—2. The amount and variability of crop harvest across households in the year 2009.

Abbreviations: kg/ae/d, kilograms per adult equivalent per day.
Note 1: Results are presented on a logarithmic (to the base of 10) scale.
Note 2: Households with 0 production of the crop were excluded from data presented in this figure (but included in analysis) to demonstrate harvest variability among households that managed to produce the crop.

Table 4—1. Characteristics of households, children, and villages.

Characteristics	Median or mean* (25th, 75th centile) or counts (%)
Household characteristics (n=545)	
No. of people	9 (6, 14)
Adult equivalents	7 (4, 10)
Wealth	
Level 1 (poorest)	122 (23%)
Level 2	136 (25%)
Level 3	138 (26%)
Level 4 (wealthiest)	104 (19%)
Unclassified	45 (8%)
≥1 member occupied outside agriculture	167 (31%)
Garden produce harvested	383 (70%)
Cash crops harvested	431 (79%)
Food crops harvested	542 (99%)
Crop yield (kg/ae/year) [a]	
Millet	113 (53, 190)
Sorghum	131 (70, 208)
Maize	18 (6, 42)
Fonio	5 (0, 18)
Rice	0 (0, 24)
Cotton	0 (0, 56)
Sesame	33 (14, 68)
Peanut	21 (5, 53)
Food energy equivalent (kcal/ae/d):	
food crops	2,439 (1,609, 3,769)
<2,900 kcal/ae/d	321 (59%)
food & cash crops	3,211 (1,965, 5,483)
<2,900 kcal/ae/d	238 (44%)
Children's characteristics (n=975)	
Age	
0 – <6 months	464 (48%)
6 months – <2 years	222 (23%)
2 years – 5 years	289 (30%)
Sex	
Male	476 (49%)
Female	499 (51%)
MUAC [b]	135* (130, 140)
Month of MUAC measurement	
March	131 (13%)
April	133 (14%)
May	208 (21%)
June	265 (27%)
July	139 (14%)
August	99 (10%)
Village characteristics (n=52)	
Infrastructure level	
Level 1 (lowest)	32 (62%)
Level 2	14 (27%)
Level 3	4 (8%)
Level 4 (highest)	2 (4%)
Has a market	20 (37%)

Abbreviations: MUAC, middle-upper arm circumference; kcal/ae/d, kilocalories per adult equivalent per day.

[a] 0 production values present when crop was not cultivated, or its harvest failed.

[b] MUAC data in the table is presented for all children included in the analyses, aged 0–5 years.

Median food energy value of household food crop harvest was below the recommended kcal intake of 2,900 kcal per day for moderate activity levels of our assumed adult equivalent (a 30–60 years old male) (Table 4–1). 62% of the children lived in households that produced less food energy from their food crop harvest than was recommended for their households for moderate activity levels and 55% less than recommended for light activity [49]. 32% of the children lived in households that produced less food energy from their combined food and cash crop harvest than was recommended for their households for moderate activity and 25% less than recommended for light activity [49].

Average MUAC among children of 0–5 years of age was 135 mm. Among children aged 6 months–5 years, 3% had MUAC<115 mm and 10% MUAC between 115 & 125 mm, indicating the proportions of severe and moderate acute undernutrition respectively (Tables 4–1 and 4–2).

Table 4—2. The number of children with MUAC <115 mm and 115–125 mm (values signifying severe and moderate acute undernutrition only in the age group 6 months – 5 years).

MUAC	**Number of children (%)**	
	<6 months (n=464)	**6 months–5 years** (n=511)
<115mm	82 (18%)	16 (3%)
115–125mm	86 (19%)	51 (10%)

Relationship between MUAC and crop harvests

The relationships between MUAC and the two measures of annual household per capita crop harvest (kcal/ae/d), E_f and E_{fc}, are shown in Figure 4–3. These plots suggest that children's MUAC decreased at crop yields below around 3,000 kcal/ae/d. The children's MUAC was 2.49 (95% CI 0.45, 4.52) mm less at 1,000 than at 3,000 kcal/ae/d when food energy estimates were based on cereal food crop production alone (E_f), and 1.99 (95% CI 0.27, 3.69) mm less when food energy estimates were based on food and cash crop production combined (E_{fc}) (Table 4–3).

Piecewise linear models with a change point at 2,900 kcal/ae/d suggest that below 2,900 kcal/ae/d, MUAC decreased by 1.29 (CI 95% 0.15, 2.42) mm per 1,000 kcal/ae/d decrease in household food energy production from cereal food crops only (E_f), and by 1.55 (CI 95% 0.30, 2.81) mm per 1,000 kcal/ae/d decrease in food energy from food and cash crop harvest combined (E_{fc}) (Table 4–3).

These results were largely insensitive to the exclusion of observations with high crop production values (see Supplementary Table 4–6 at the end of this chapter) and the additional adjustment for crop failure (last line of Table 4–3).

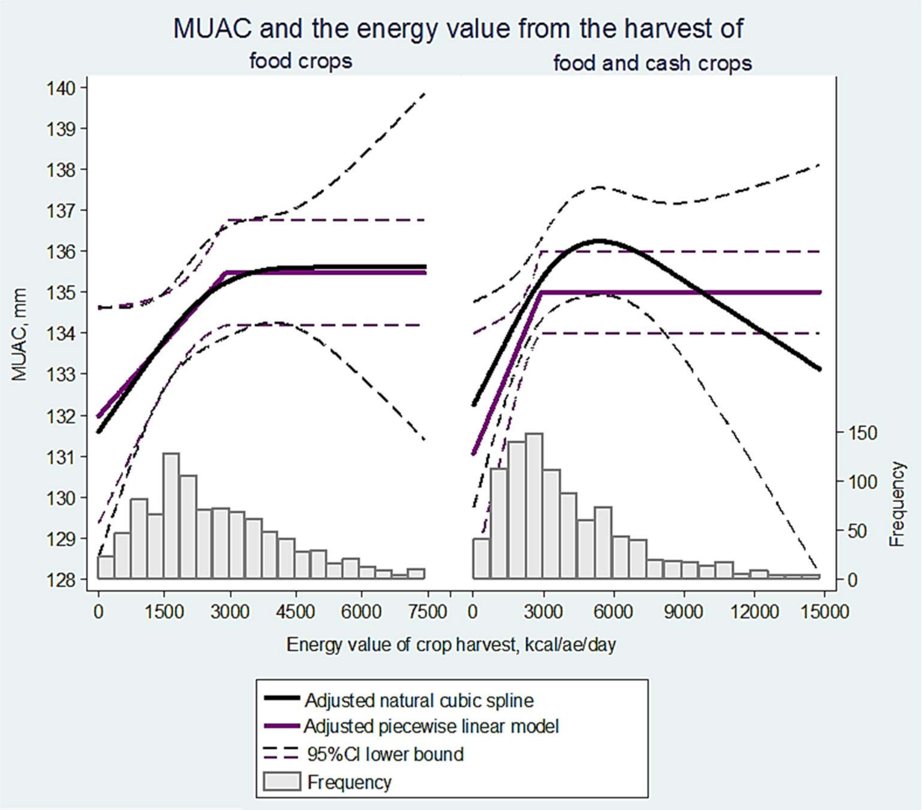

Figure 4—3. Restricted natural cubic spline and piecewise linear models of the associations of children's MUAC with food energy production.

On the left: food energy estimates are based on food crop harvest alone.
On the right: food energy estimates are based on food and cash crop harvest combined.
Abbreviations: CI, confidence interval; kcal/ae/d, kilocalories per adult equivalent per day; MUAC, middle-upper arm circumference; HDSS, Health and Demographic Surveillance System.
Note 1: For purposes of clarity in the visual presentation, we excluded from the models the sparse observations at the highest exposure values: 40 observations excluded within 8,000–16,052 kcal/ae/day interval of the energy production from food crop harvest and 14 observations were excluded within 15,000–34,064 kcal/ae/day interval of the energy production from both food and cash crops combined.
Note 2: Both models were adjusted for age, sex, month of MUAC measurement, household wealth, non-agricultural occupation, garden produce, village infrastructure, and market presence.

Table 4—3. Estimated differences in MUAC (mm) per difference in food energy production from crop harvest.

Model adjustments	Reduction in MUAC (95% CI) at 3,000 *vs* 1,000 kcal/ae/d [a]:		Reduction in MUAC (95% CI) for a 1,000 kcal/ae/d decline in crop harvest below 2,900 kcal/ae/d [b]:	
	food crop harvest alone	food & cash crop harvest combined	food crop harvest alone	food & cash crop harvest combined
Model 1: unadjusted	2.44 (0.14, 4.73)	2.01 (0.12, 3.90)	1.27 (-0.01, 2.55)	1.64 (0.22, 3.05)
Model 2: adjusted for children's age, sex, and month of MUAC measurement	2.67 (0.58, 4.76)	1.98 (0.26, 3.71)	1.44 (-0.27, 2.60)	1.57 (0.29, 2.85)
Model 3: model 2 + adjustments for household wealth, non-agricultural occupation, garden produce, village infrastructure, and market presence	**2.49 (0.45, 4.52)**	**1.99 (0.27, 3.69)**	**1.29 (0.15, 2.42)**	**1.55 (0.30, 2.81)**
Model 4: model 3 + adjustment for failure to harvest at least one of the cultivated crops	2.49 (0.46, 4.53)	1.97 (0.26, 3.67)	1.29 (0.15, 2.43)	1.57 (0.31, 2.83)

Abbreviations: CI, confidence interval; MUAC, middle-upper arm circumference; kcal/ae/d, kilocalories per adult equivalent per day.

[a] Estimates based on models with natural cubic splines.

[b] Estimates based on piecewise linear models.

Table 4—4. Adjusted estimates of differences in MUAC (mm) per specified difference in food energy production from crop harvest by sex.

Sex	No. (%)	Mean MUAC, mm	Mean food energy from food crop harvest, kcal/ae/d	Difference in MUAC (95% CI): 3,000 *vs* 1,000 kcal/ae/d [a]		Reduction in MUAC (95% CI) for a 1,000 kcal/ae/d decline in crop harvest below 2,900 kcal/ae/d [b]:		
				food crop harvest alone	food & cash crop harvest combined	food crop harvest alone	food & cash crop harvest combined	p-value for inter-action [b]
All children	975 (100)	135	2,978	2.49 (0.45, 4.52)	1.99 (0.27, 3.69)	1.29 (0.15, 2.42)	1.55 (0.30, 2.81)	
Boys	499 (51)	136	3,094	3.81 (0.84, 6.77)	3.47 (0.97, 5.96)	2.15 (0.49, 3.80)	2.43 (0.56, 4.30)	0.203
Girls	476 (49)	133	2,842	0.99 (-1.81, 3.78)	0.86 (-2.13, 2.57)	0.42 (-1.14, 1.99)	0.69 (-1.02, 2.40)	

Abbreviations: CI, confidence interval; MUAC, middle-upper arm circumference; kcal/ae/d, kilocalories per adult equivalent per day.

[a] Estimates based on models with natural cubic splines.

[b] Estimates based on piecewise linear models.

There was no clear evidence that the decrease in MUAC with lower household food crop yields was different in boys *vs* girls (Table 4–4, p=0.203 for statistical interaction), but the point estimates of the decrease were slightly larger in boys. Boys' MUAC was 3.81 (0.84, 6.77) mm lower at 1,000 than at 3,000 kcal/ae/d when food energy estimates were based on cereal food crop production alone (E_f), and 3.47 (95% CI 0.97, 5.96) mm less when food energy estimates were based on food and cash crop production combined (E_{fc}). The corresponding figures for girls were 0.99 (-1.81, 3.78) mm, and 0.86 (95% CI -2.13, 2.57) mm.

In line with these results, Supplementary Table 4–7 (at the end of this chapter) shows that the prevalence of acute undernutrition (MUAC <125 mm) was slightly higher in households with ≤2,900 kcal/ae/d food cereal crop energy production (p-value=0.093). Such households also had less crop diversity (as reflected in the number of different crops harvested) and they less frequently produced cash crops and garden produce (p-value<0.001). Their household size was slightly larger (p-value <0.001), and they more frequently had at least one member of their household involved in a non-agricultural occupation (p-value<0.002).

Discussion

This is one of the few studies which examines the association between children's nutritional status and household cereal crop production. Its results suggest that low household production of food energy from cereal crops is associated with lower MUAC for children ≤5 years of age.

The results of the restricted spline plot suggest a decline in MUAC below around 3,000 kcal/ae/d, which is broadly consistent with the recommended energy intake of 2,900 kcal/d for a moderately active man of 30–60 years of age [49,50]. The results of the linear spline model show a statistically significant decline in MUAC very similar in gradient to that of the restricted spline plot when the change point was fixed *a priori* at 2,900 kcal/ae/d.

Our findings are consistent with some [22–24] but not all [20,21] studies examining the association between children's nutritional status and household level measures of agricultural production. Variation in findings across different studies may be explained by different contexts [20], choice of nutritional status measures and temporality of their association with crop harvest (e.g., acute *vs* chronic undernutrition [20]), and other modifying factors.

We did not find clear evidence of a gender difference in the association of crop production with children's nutritional status. Our findings suggest a possibly more pronounced association among boys than girls. This could in part be related to the higher level of child undernutrition among boys than girls in our setting [57]. Given the relatively small study sample, we cannot conclude a difference, but the point estimates were larger in boys than girls.

The current study was conducted in a population whose livelihood is likely to be particularly vulnerable to crop failure and low cereal crop productivity. Over half of the examined children lived in households whose food crop production in the year 2009 was not sufficient to meet their energy needs for even light activity. A quarter of households would not be able to reach their energy requirements for light activity levels even when selling all their cash crops and purchasing millet instead. The association between low levels of household crop harvest and acute child undernutrition is highly plausible in such context.

We must note that the MUAC measurements analysed in this study were made in the six nutritionally more challenging months of the year in the study area, as they include the period when household cereal stocks from the last harvest start to run low (the time often referred to as the 'lean' or the 'hunger' season) [58]. Analysis of MUAC data collected evenly throughout the year may yield a lower magnitude of the examined association.

The high proportion (14%) of acute undernutrition among children in our study population is of *serious public health significance*, according to the WHO guidelines [59]. The prevalence of acute undernutrition above 10% is not uncommon in many low- and middle-income countries in Africa, South and South-East Asia [60]. Similar analyses of the association between household crop production and children's nutritional status in other countries in these regions would help to identify whether household crop production levels in these settings also incur a risk for children's nutritional health.

Our study population and similar populations may be vulnerable to the adverse effects of climate change on agricultural productivity. Given that the association between children's nutritional status and household crop harvest was identified even in a year of average agricultural productivity and given the evidence of the link between weather-related area-wide crop failures with negative nutritional outcomes among children in similar settings [30,31,61–66], it is likely that the Nouna HDSS population would experience greater levels of acute child undernutrition in years of low agricultural productivity. Droughts are already recognised as the top natural disaster in Burkina Faso and their frequency and severity is projected to increase with climate change, potentially leading to increased episodes of low crop yields [67–69].

However, our estimates were based on harvest differences across households in a single year with average crop productivity. According to Annual National Agricultural Survey data, over the five years preceding the harvest year of our study crop yield in Kossi province did not fall below the average yield level calculated over the period of 1984–2014 [70]. Therefore, our estimated magnitude of change in children's MUAC per difference in food energy from household crop harvest is only applicable to average yield levels, and should not be used to infer the possible change in children's MUAC in response to inter-annual changes in household harvest, particularly those resulting from drought or other exogenous shocks. However, the identified association in a year of average crop productivity does suggest the likely vulnerability of our study population to weather-related and other declines in crop yield.

We used the indirect measure of food energy production from crop harvest to approximate household food energy availability. Our measure did not take into account other food sources possibly acquired by households (e.g., food purchases, gifts, and loans [71]) or disposal of the produce (e.g., transfers to others and food waste). Apart from household food energy availability, children's food intake is subject to intra-household food distribution and children's food preferences; children's nutritional status, apart from food intake, is also determined by their health condition and other factors [4]. Furthermore, we used household harvest data reported by the head of household. In the socio-cultural context of our study, the head of household is the key informant on the amount of crop harvest. However, reported data (as opposed to quality-controlled measurements or observations made by data collectors, which in our study area were not available) may have some inconsistencies, including the risk of under- or over-reporting.

In our analyses, it was not possible to account for crop harvest that households produced in years preceding or following the year 2009, as there were no data collected. Such information could help to adjust for any effect of crop harvest on children's MUAC prior to the year 2009 and for any cereal stock remaining from a preceding year that households could consume in addition to the crops harvested in the year 2009. However, differences in child MUAC in the year 2010 related to household crop harvest in years preceding 2009, if any present at all, would be minor, as MUAC is sensitive to short-term changes in food intake. The influence of previous harvests on our examined MUAC measurements was likely to have been superseded by the influence of the harvest of the year 2009. The harvest of 2010 could have some influence on food intake in August 2010, if any of the households started the harvest of 2010 earlier than September, as assumed in our analyses. This was also impossible to account for due to the lack of information on when individual households started their harvest in the year 2010.

Other minor limitations include: (1) our adult equivalent calculations were based on the number of household members at the time of the harvest of 2009, and hence, did not account for any possible changes in household composition between the harvest time and the time of child MUAC measurement (March–August 2010), (2) food price estimates were based on a single time point (December 2009, when crop sales occur frequently) for the Nouna market, as the largest market in the study area [72], hence, we did not account for any fluctuations in food price across the year.

Conclusion

MUAC measurements made during the months of March–August following a 'normal' harvest year, indicate negative impacts of low household cereal crop yields on child nutrition in this rural subsistence farming population of Burkina Faso.

The results suggest that this and similar populations may be adversely affected by low levels of crop harvest and vulnerable to the adverse effects of weather and other factors on household crop yields, especially in the context of climate change. Nutrition-sensitive monitoring of household crop yields and support provision to the most vulnerable households in such settings could aid the achievement of the SDG No. 2 in the face of the projected climate change impacts on agricultural productivity.

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Supplementary material

Note on study subject representativeness

Although our study subjects were not randomly selected from the Nouna HDSS population, their demographic and socio-economic characteristics, except age, did not differ from the characteristics of children 0–5 years of age in all Nouna HDSS population, as recorded during the census of the year 2009 (Table 4–5).

Table 4—5. Characteristics of the study subjects *vs* population of children ≤5 years of age in the Nouna HDSS system.

	Study subjects % (n)	**Population (census) % (n)**
Children's characteristics	**n=975**	**n=17,112**
Age		
0 – <6 months	48 (464)	6 (1,009)
6 months – <2 years	23 (222)	29 (4,916)
2 years – 5 years	30 (289)	65 (11,187)
Sex		
Females	51 (499)	50 (8,518)
Males	49 (476)	50 (8,594)
Household characteristics	**n=545**	**n=7,695**
At least one member with occupation outside agriculture	31 (301)	34 (2,638)
Wealth		
Level 1 (poorest)	23 (122)	22 (1,727)
Level 2	25 (136)	22 (1,687)
Level 3	26 (138)	22 (1,690)
Level 4 (wealthiest)	19 (104)	20 (1,544)
Unclassified	8 (45)	14 (1,047)
Village-level characteristics	**n=52**	**n=59**
Village infrastructure		
Level 1 (lowest)	62 (32)	63 (37)
Level 2	14 (14)	27 (16)
Level 3	8 (4)	8 (4)
Level 4 (highest)	4 (2)	3 (2)
Has a market	37 (20)	37 (22)

Abbreviations: HDSS, Health and Demographic Surveillance System; n, number.

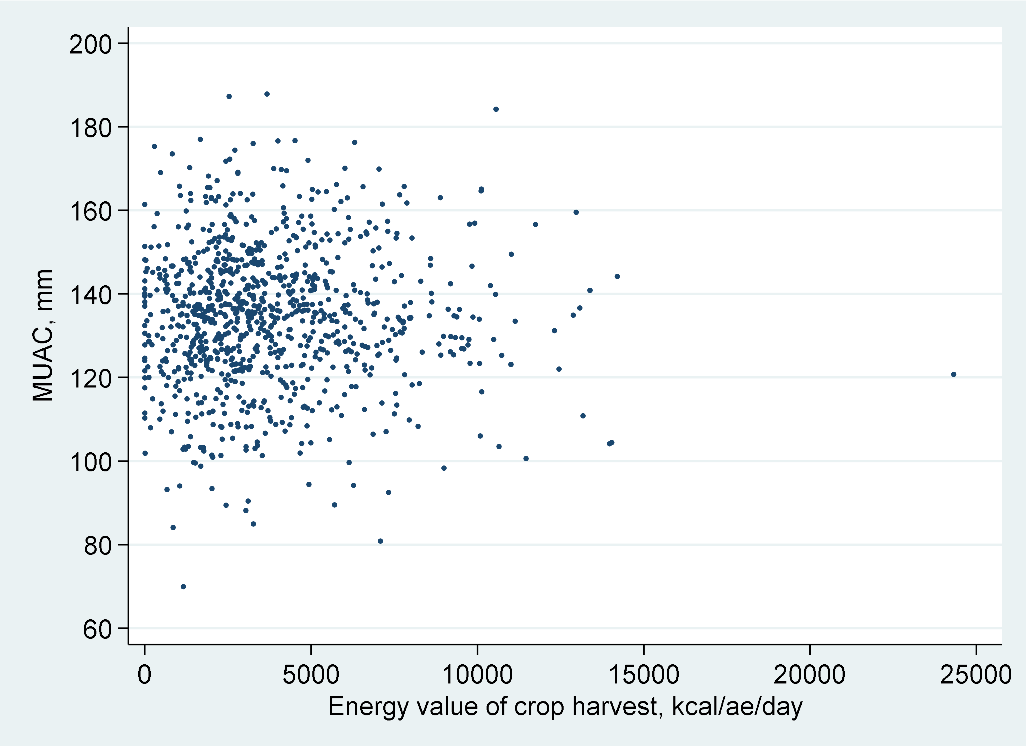


Figure 4—4. Scatter plot of the analysed child MUAC data *vs* the energy value of their household food crop harvest.

Sensitivity Analysis I: exclusion of observations with high crop production values

This sensitivity analysis assessed the impact of the exclusion of observations with high crop production values (>8,000 kcal/ae/d from food crop harvest and >15,000 kcal/ae/d from food and cash crop harvest combined), which are implausible for the scale of subsistence farmers' production. These exclusions were also made for the purpose of clarity in the visual presentation of the Figure 4–3.

Table 4—6. Estimated differences in MUAC (mm) (95% CI) per difference in food energy production from crop harvest.

Model adjustments	**Reduction in MUAC (95% CI) at 3,000 *vs* 1,000 kcal/ae/d** [a]**:**		**Reduction in MUAC (95% CI) for a 1,000 kcal/ae/d decline in crop harvest below 2,900 kcal/ae/d** [b]**:**	
	food crop harvest alone	food & cash crop harvest combined	food crop harvest alone	food & cash crop harvest combined
Model 1: unadjusted	2.63 (-0.07, 5.94)	2.19 (0.11, 4.28)	1.26 (-0.03, 2.56)	1.69 (0.27, 3.11)
Model 2: adjusted for children's age and sex, and month of their MUAC measurement	2.70 (0.24, 5.16)	2.22 (0.33, 4.11)	1.42 (0.24, 2.61)	1.60 (0.31, 2.88)
Model 3: model 2 + adjustments for household wealth, non-agricultural occupation, garden produce, village infrastructure, and market access	**2.49** **(0.09, 4.89)**	**2.34** **(0.47, 4.22)**	**1.29** **(0.13, 2.45)**	**1.56** **(0.29, 2.82)**
Model 4: model 3 + adjustment for failure to harvest at least one of the cultivated crops	2.50 (0.11, 4.91)	2.35 (0.48, 4.22)	1.29 (0.13, 2.45)	1.57 (0.30, 2.84)

Abbreviations: AIC, Akaike Information Criterion; CI, confidence interval; MUAC, middle-upper arm circumference; kcal/ae/d, kilocalories per adult equivalent per day.

[a] Estimates based on the natural splines

[b] Estimates based on piecewise linear models; presented are model estimates for the interval of food energy <2,900 kcal/ae/d

[c] Estimates based on piecewise linear models; presented are model estimates for the interval of food energy <1,000 kcal/ae/d

Table 4—7. Characteristics of the study population in relation to food energy production from food crops.

Characteristics	Counts (column %) or median (IQR)			
	≤2,900 kcal/ae/d	>2,900 kcal/ae/d	p-value	df
Household production related characteristics [a]				
Cash crops harvested	231 (72)	200 (89)	<0.001	1
Garden produce harvested	207 (64)	176 (79)	<0.001	1
No. of different crops harvested				
1	37 (12)	9 (4)	<0.001	6
2	71 (22)	17 (8)		
3	86 (27)	57 (26)		
4	73 (23)	77 (34)		
5	44 (14)	33 (15)		
6	8 (3)	27 (12)		
7	2 (1)	4 (2)		
Other household characteristics [a]				
No. of people	11 (7, 16)	8 (5, 12)	<0.001	1[d]
Adult equivalents	8 (5, 12)	6 (3, 8)	<0.001	1[d]
At least one member with occupation outside agriculture	115 (35)	52 (23)	0.002	1
Wealth				
Level 1 (poorest)	72 (22)	52 (23)	0.240	4
Level 2	83 (26)	53 (24)		
Level 3	76 (24)	64 (29)		
Level 4 (wealthiest)	71 (22)	36 (16)		
Unclassified	20 (6)	18 (8)		
Village-level characteristics [a]				
Village infrastructural development				
Level 1 (lowest)	117 (36)	77 (34)	0.047	3
Level 2	72 (22)	68 (30)		
Level 3	40 (12)	34 (15)		
Level 4 (highest)	92 (29)	45 (20)		
Have a market in their village	205 (64)	143 (64)	0.995	1
Village				
Nouna	78 (24)	29 (13)	0.048	51
Kodougou	17 (5)	2 (1)		
Bagala	4 (1)	2 (1)		
Dara	3 (1)	4 (2)		
Ley	2 (1)	1 (1)		
Children's characteristics [b]				
Age				
0 – <6 months	272 (48)	192 (48)	0.999	2
6 months – <2 years	130 (23)	92 (23)		
2 years – 5 years	169 (30)	120 (30)		
Sex				
Females	273 (48)	226 (56)	0.012	1
Males	298 (52)	178 (44)		
Nutritional status [c]				
MUAC<115mm	7 (2)	9 (4)	0.093	2
115mm<MUAC<125mm	36 (13)	15 (7)		

Abbreviations: df degrees of freedom, MUAC middle-upper arm circumference, kcal/ae/d kilocalories per adult equivalent per day

[a] Statistics in this section of the table are based on household-level observations (n=545)

[b] Statistics in this section of the table are based on child-level observations (n=975)

[c] Counts (%) based on observations of children of 6 months–5 years of age, the age group where the presented MUAC cut-off values signify severe (MUAC<115 mm) and moderate (MUAC 115–125 mm) acute undernutrition.

[d] Based on the non-parametric Mood’s median test, chosen as the data was not normally distributed.

4.2. Commentary on Paper 2 *Household harvest and child MUAC*

The principal finding of this chapter (published in Belesova et al. Environ Health 16(1):65, 2017) was a (non-linear) association of food energy from household crop harvest with MUAC in children ≤5 years of age. It suggested that low crop harvest was associated with lower child MUAC in households that produced less than 3,000 kcal/ae/d from their crop harvest. No evidence for such association was found in households with food energy from cereal crop harvest exceeding 3,000 kcal/ae/d. (In relation to the exposure of combined food and cash crop harvest, despite some decline in mean MUAC with higher levels of crop harvest above 3,000 kcal/ae/d, visible in Figure 4–3, confidence intervals were so wide that they were compatible with both a higher or lower child MUAC corresponding to higher levels of crop harvest.)

A number of methodological issues of this paper are worthy of comment in relation to this thesis.

(i) Cross-sectional analysis

The basis of these analyses was a cross-sectional comparison of household crop harvest and a nutritional outcome. This study design was selected because household level crop harvest data in the Nouna HDSS has been collected only in one year. Harvest differences across households in the same year may not have the same effect on children's nutritional status as changes in the harvest level from one year to another. Households could have developed certain strategies to cope with their general harvest levels. Such strategies may differ from those that households employ when they harvest lower amounts in one year than another. It is thus a somewhat indirect method of addressing the question of whether *year-to-year* variation in food crop availability affects the nutritional status of children, for example, as a consequence of unfavourable weather conditions during the growing season. Nevertheless, it informs on whether food availability from household crop harvest could be a determinant of children's nutritional status in this setting.

(ii) Year of average yield

The cross-sectional association was examined and identified in a year (2009) of average crop yield (as determined from the provincial crop yield time series over the period from 1984–2012). In a year with different crop yields, the household harvest, coping strategies, and other contextual factors may differ, and hence the shape of this association and might be different. Therefore, the estimated magnitude of change in child MUAC per difference in food energy availability from household crop harvest from these analyses may not be applicable to a year with another crop yield level. Yet the evidence for the association identified in these analyses suggests that in the Nouna HDSS, children's nutritional status could be vulnerable to household harvest levels even in a year of average crop yield. Thus, it could also potentially be vulnerable to yield reductions below the period average level of yield.

(iii) Need for control of confounding, esp. socio-economic parameters

Cross-sectional differences in children's MUAC, in addition to differences in their household crop harvest, could also be explained by socio-economic differences. To minimize influence of such alternative explanations, analyses were controlled for the following potential confounders: children's age, sex, and month of MUAC measurement, household wealth, non-agricultural occupation, garden produce, village infrastructure, and market presence. Residual, i.e., unmeasured, confounding might still have resulted from such factors as (i) ill-health or death of a family member who participates in crop cultivation and also cares for and feeds children, (ii) socio-economic aspects not fully covered by the wealth index, e.g., land ownership, debt obligations, mother's marital status, and other factors, (iii) cultural differentials within the study population simultaneously related to crop production and caring for children or intra-household food distribution. Some of these factors are likely to be closely correlated with the factors that the analyses were controlled for, and hence, may not have confounded the identified association, although the possibility of residual confounding in these analyses cannot be excluded.

(iv) Use of a proxy for food availability

Household food availability in this analysis was indirectly approximated by the energy value of their cereal crop harvest, which did not consider other food transfers, e.g., crop harvest sales, in-kind contributions, and food purchases. 31% of the examined households engaged in income-generating activities other than agriculture, which could have provided income for food purchases. However, evidence for the association of child MUAC with food energy from household harvest was strong even after adjusting for factors approximating differences in other food sources across households (presence of a market, wealth, other income-generating activities). The energy equivalent of crop harvest in a small fraction of households examined in these analyses reached 16,052 kcal/ae/day, which is unlikely to reflect the actual amount of food energy consumed in these households – presumably this reflects the few households engaged in crop production for trade purposes or those employing agricultural labourers who are paid in grain. The shape of the association cannot be precisely determined, but it suggested a reduction in MUAC in households that produced less than 3,000 kcal/ae/d, which is consistent with the recommended energy intake for the adult equivalent [129]. Thus, the energy value of the household crop harvest may serve as a better proxy in households with low harvest production levels than high production levels, potentially because in these households harvest is a more direct proxy of food availability and intake.

Furthermore, data on household harvest was reported by the head of household and was potentially subject to error and bias, e.g., arising from non-standard harvest units, lack of accounting for in-kind payments, conscious over- or under-reporting (e.g., over-reporting may occur when interviewers originate from the same community as the interviewees, who then may have an incentive to appear more agriculturally "successful" in front of their "neighbours"; under-reporting may occur when interviewees might hope for some form of support from the researchers), accuracy of recall, illiteracy, and inherent lack of knowledge of the amount harvested [130]. In addition to household food availability, children's food intake is further subject to intra-household food distribution and children's food preferences; children's nutritional status, apart from food intake, is also determined by their health condition and other factors [21].

Despite the indirectness and possible limitations of this measure, results suggested that it has a reasonably strong association with children's MUAC, adjusted for a comprehensive set of confounders. This may suggest that the identified association could be even stronger if a more direct proxy of food availability was used.

(v) Other food produce

The five food crops (millet, sorghum, maize, fonio, and rice) considered in these analyses were not the only food produce in most of the examined households. 99% of the households cultivated some of or all of the five cereal food crops, which are mainly intended to meet their subsistence needs. Although 70% of the households also cultivated other food produce, such as vegetables and salad produced in their gardens, there was no evidence for an association of children's MUAC with an indicator for the presence of garden produce, when adjusted for other factors. On the contrary, the association of MUAC with food energy from cereal harvest remained significant after adjusting for an indicator of the presence of garden produce. Hence, presence of garden produce may not significantly contribute to explaining children's MUAC. Such a result is plausible given the low proportion which these products contribute to the average food intake in Burkina Faso (e.g., 0.44% of daily calorie intake from vegetables) [122]. 79% of the households also cultivated some cash crops (cotton, sesame, or peanuts), mainly to cover their day-to-day expenses, including any additional food purchases. However, even the maximum amount of grain purchases that could be made using income from their cash crop sales would still have not been sufficient to provide the recommended level of food energy even for light activity levels in a quarter of the households. The association of MUAC with cereal crop harvest remained significant also when incorporating the hypothetical energy value of the household cash crop harvest (expressed as the value of food energy that a household could acquire if it sold all of its cash crop harvest and used all income from these sales to purchase millet). A number of the households owned livestock, which theoretically also could be used as a source of food. However, meat is rarely consumed in this setting, with national per capita meat consumption constituting only 3.18% of daily kilocalorie intake [122]. Instead of consumption, livestock is mainly maintained as a wealth asset, which can be sold in times of hardship to acquire cash for grain purchases [131]. Therefore, analyses were not separately adjusted for livestock ownership. Instead, livestock ownership data was used as an input for the household wealth index, which the analyses were adjusted for. A potential limitation of this approach is the lack of account for possible differences in household access to food products, other than meat, that can be generated from livestock and consumed by children (e.g., milk and animal blood). Yet, consumption of such foods appears to be low. It is estimated that only 26% of children in Nouna HDSS consumed cattle milk [132]. I did not identify any accounts of animal blood consumption neither in literature on Burkina Faso nor in my context exploration when visiting Nouna.

Overall, the findings suggest that household harvest of these five cereal food crops alone could be a reasonable proxy determinant of children's nutritional status in the Nouna HDSS area.

(vi) Uncertainty around the shape of the association

The shape of the identified association is not precisely defined by my analysis but is broadly compatible with knowledge of the food energy requirements for human nutrition. I used two approaches to characterise the shape of the association: models with natural cubic splines and piecewise linear models. The flexible data-driven approach of models with cubic splines indicated that low child MUAC was associated with low household crop harvest for those households in which crop harvest provided less than approximately 3,000 kcal/ae/d (around half of the examined households). There was some uncertainty around the shape of the association when modelled using a linear piecewise model. I first examined the location of the change point by the lowest AIC value. This approach suggested a slightly lower AIC value with the change point placed at 1,000 kcal/ae/d. However, AIC values within the range of 500 to around 4,000 kcal/ae/d differed to a minor extent, suggesting considerable uncertainty around the precise location of the change point. The uncertainty could be related to a measurement error in the harvest data and/or the fact that the number of child MUAC observations at the lowest level of household crop harvest was small. Therefore, I chose to present linear piecewise models with the *a priori* chosen threshold of 2,900 kcal/ae/d (i.e., the recommended level of energy intake for the adult equivalent [129]), ensuring compatibility between the two modelling approaches.

4.3. Consistency with other evidence

I am not aware of other studies that specifically related child MUAC to household level measures of crop production. A small number of studies related various measures of household crop production to other measures of child nutritional status than MUAC (weight-for-age, height-for-age, weight-for-height, skinfold measurements, haemoglobin and haematocrit levels) [85–89] (Table 4–8). A study in El Salvador suggested an association between the children's height-for-age index with the area of land cultivated by their households, but it was not adjusted for important confounders [85]. Studies in Zambia (low risk of confounding) and Nepal (probably high risk of confounding) suggested associations of height-for-age and weight-for-height indices with crop harvest quantity and yield as well as agricultural income

Table 4—8. Table of evidence from studies that examined household crop production in relation to child nutritional status (based on Table 2–6).

Source	Country	Study design	Exposure measure	Outcome measure	Sample size	Age, years	Risk of confounding	Key results
Brentlinger *et al*, 1999 [85]	El Salvador	cross-sectional	area of land cultivated	Ht/Age	761 children	<5	- Probably high risk of confounding, as the study accounted for some but not all the important potential confounders	- Smaller area of redistributed land cultivated associated with higher risk of stunting (OR for stunting per additional hectare of cultivated land 0.64, 95% CI 0.44, 0.93)
Kaufman, 2008 [86]	Northern Laos	cross-sectional	rice harvest	Ht/Age	600 & 892 children	<5	- High risk of confounding due to limited confounder adjustment	- Rice yields were not statistically significantly associated with child stunting (*article did not report numerical estimates*)
Kumar *et al*, 2015 [87]	Zambia	cross-sectional	quantity and income from agricultural production	Ht/Age, Wt/Ht	3,340 households	0.5–5	- Low risk of confounding, as the study accounted for most important potential confounders	- Among children 6–23 months of age: no evidence for associations of agricultural production or income with the anthropometric indices - Among children 24–59 months of age: one log unit increase in agricultural production quantity (kg) and income were associated with 0.020 ($p<0.01$) and 0.017 ($p<0.006$) unit increase in Ht/Age Z-score and with 0.2 ($p<0.05$) and 0.1 ($p<0.05$) percentage point increase in wasting (Wt/Ht Z-score<-2 SD), respectively
Shack *et al*, 1990 [88]	Papua New Guinea	cross-sectional	quantity of crops cultivated (count of plants); income from cash crop sales	Wt/Age, Ht/Age, Wt/Ht, skinfolds, arm circu., Hbg, Htc	56 families	≤6	- Probably low risk of confounding, as the study accounted for most but not all important potential confounders	- An increase in income from cash crops by 1 kina/month was associated with an increase of 0.03 points ($p<0.01$) and 0.02 points ($p<0.01$) in child Ht/Age and Wt/Age scores, and 0.03 cm ($p<0.05$) increase in child arm circumference; there was no evidence for statistically significant associations with child Wt/Ht, Hbg, Htc - The quantity of food crop planted was not significantly associated with indicators of child nutritional status
Shivley & Sununtnasuk, 2015 [89]	Nepal	crop yield, area of land cultivated	cross-sectional	Ht/Age	1,769 children	<5	- Probably high risk of confounding, as the study accounted for some but not all the important potential confounders	- Among children ≥2 years: a 1,000 kg/ha increase in crop yield was associated with 0.0457 point increase in Ht/Age Z-score ($p<0.05$) and a reduction in the risk of stunting by about 2%, no evidence for associations of these measures with farm size - Among children <2 years of age there was no evidence for any of these associations

among children 2–5 years of age but not among children <2 years [87,89]. In contrast, a study in Northern Laos provided no evidence for the association of the child height-for-age index with household rice harvest (high risk of confounding) [86]. Similarly, a study in Papua New Guinea (probably low risk of confounding), found no evidence for the association of child nutritional status with the amount of crops cultivated by households [88]. The limited degree of consistency among these findings could be explained by differences in the measures of household crop production (e.g., area of cultivated land *vs* income from crop sales), choice of nutritional status measures and temporality of their association with crop harvest (e.g., acute *vs* chronic undernutrition [86]), differences in the pathways linking crop harvest and child nutritional status (e.g., consumption pathway *vs* 'entitlement' pathways, see Figure 1–2), differences in the methodological quality of studies (e.g., high *vs* low risk of residual confounding), different study contexts, and other potential modifying factors. Furthermore, none of these studies examined MUAC as the outcome measure, limiting their direct comparability with results of this chapter.

To strengthen evidence for conclusions concerning the causality of low household crop harvest as a determinant of child undernutrition, further studies are required in other settings as well as in the Nouna HDSS in years with other levels of agricultural productivity. Nevertheless, it is fairly likely that the association is causal in the Nouna HDSS area, given all of the following: the importance of subsistence crop production [133] and cereals as a key source of energy in local diets [122], and the recognition of MUAC as a measure of child nutritional status, which is used to diagnose acute undernutrition [81,82,134,135].

4.4. Implications of Paper 2 *Household harvest and child MUAC*

Given the somewhat indirect nature of the evidence provided by this study with regards to the aim of this thesis, it is pertinent to consider what it tells us about vulnerability to the health and the nutritional risks of interannual variations. If the identified association is causal, it suggests that, even in the conditions of average agricultural yield, in the Nouna HDSS there are households which do not produce an optimal quantity of cereal crop harvest for their nutritional needs. Among these households, children with lower access to food energy from their household harvest have poorer nutritional status. Therefore, low crop harvest in this population appears to be one of the determinants of child nutritional status, as measured by MUAC.

MUAC is a well-recognized anthropometric proxy of nutritional status among children of 6 months to 5 years of age, which is indicative of children’s short-term nutritional status and is shown to be highly correlated with weight change [136]. In this age group MUAC values <125 mm are commonly interpreted as indicative of moderate acute undernutrition and values <115 mm of severe acute undernutrition [81,82,134,135]. Among the examined households producing ≤2,900 kcal/ae/d from their food crop harvest, 15% of children had MUAC<125 mm. This may suggest that lower harvest levels in these households were associated with MUAC declines below the level of adequate nutritional status – in other words, lower harvest in these households could be associated with child *undernutrition*. MUAC is also recognized as a strong predictor of child mortality [86,87]. As will be shown in the following chapter, in the Nouna HDSS population children with MUAC<125 mm have two times higher risk of mortality than children with higher MUAC values [129]. Therefore, if the identified association is assumed causal, low food energy availability from household crop harvest in the Nouna HDSS area may also suggest higher risk of child acute undernutrition, which might subsequently suggest a higher risk of child mortality.

Although these findings could be indirectly indicative of the vulnerability of child survival and nutrition to interannual crop yield variations, due to the cross-sectional study design, they do not contribute direct evidence of such effects. The identified cross-sectional association also does not directly inform on the possible role of weather variability for the risk of child undernutrition and mortality risk related to low crop harvest (at least not beyond the background information on the reliance of the local population on rain-fed agriculture). Direct evidence of these risks in the context of weather variation requires an examination of the association between *year-to-year* changes in crop yield with *year-to-year* changes in the risk of the outcomes of interest – child undernutrition and mortality. Such evidence could then be further analysed in relation to the possible drivers of annual crop yield variation, including weather variability and climate change.

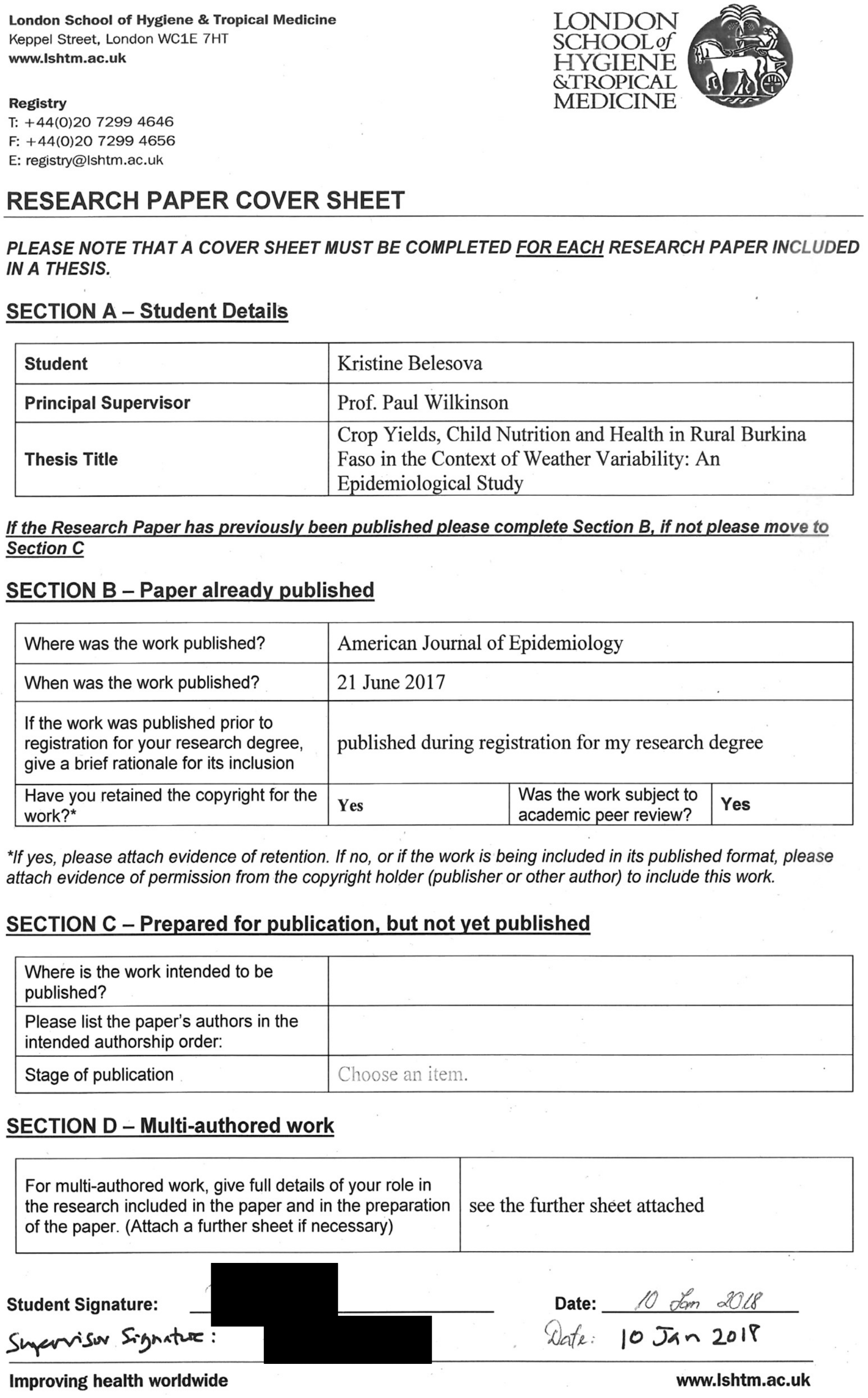
Thus, in the summary, this chapter contributed evidence of the vulnerability of children’s nutritional status measured by MUAC, to low household crop harvest in a year of average agricultural productivity in the Nouna HDSS area. If the identified association is causal, it suggests that low crop yield level in the Nouna HDSS is one of the determinants of acute child undernutrition and possibly also of the associated risk of mortality. Hence, these results warrant further examination into these risks and whether they reflect *year-to-year* changes in crop yields in Kossi province.

In the next chapter I examine the associations of annual crop yield with child MUAC and with child survival, as well as the association of child survival with child MUAC.

Chapter 5: Annual crop yield variation, child survival and nutrition

The last chapter examined the (cross-sectional) relationship between household crop harvest and children's MUAC. This chapter examines the relationships between annual crop yield, children's MUAC, and survival, addressing the second objective of the thesis to examine associations between child survival over the first five years of life, nutritional status, measured by MUAC, and inter-annual food crop yield variation. In contrast to the analysis in the last chapter, this chapter is focussed on *year-to-year* variation in both crop availability and the health outcome measures of child MUAC and mortality. Changes in food availability here are approximated in relation to the same five key cereal food crops (millet, sorghum, maize, fonio, and rice) as in Chapter 4. However, here I use crop yield (kg/ha) measured at the province level, instead of the crop harvest (kg) at the household level, which was used in the previous chapter. The results in this chapter contribute direct evidence relating to crop yield variation as a risk factor for child undernutrition and mortality in the Nouna HDSS population.

5.1. Paper 3 *Annual crop yield, survival and nutrition*



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SECTION A – Student Details

Student	Kristine Belesova
Principal Supervisor	Prof. Paul Wilkinson
Thesis Title	Crop Yields, Child Nutrition and Health in Rural Burkina Faso in the Context of Weather Variability: An Epidemiological Study

If the Research Paper has previously been published please complete Section B, if not please move to Section C

SECTION B – Paper already published

Where was the work published?	American Journal of Epidemiology		
When was the work published?	21 June 2017		
If the work was published prior to registration for your research degree, give a brief rationale for its inclusion	published during registration for my research degree		
Have you retained the copyright for the work?*	**Yes**	Was the work subject to academic peer review?	**Yes**

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Stage of publication	Choose an item.

SECTION D – Multi-authored work

For multi-authored work, give full details of your role in the research included in the paper and in the preparation of the paper. (Attach a further sheet if necessary)	see the further sheet attached

Student Signature: [redacted] **Date:** 10 Jan 2018

Supervisor Signature: [redacted] Date: 10 Jan 2018

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Section D – Multi-authored work

I conceived the idea and designed the study with advisory input from my thesis supervisor Prof. Paul Wilkinson. Prof. Paul Wilkinson reviewed the methods and Dr. Antonio Gasparrini (member of the thesis advisory committee) commented on methodological aspects of the analyses. I identified, cleaned, and linked all the necessary datasets as well as independently performed all analyses. I produced the first draft of the paper and edited it in response to co-author's comments, responded to all comments from the reviewers and editors till its publication in the *American Journal of Epidemiology*.

Student signature: Belesova 10 Jan 2018

Supervisor signature: 10 Jan 2018

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No changes were made to this manuscript post-publication, except any minor grammar and style corrections, including the change to the numbering of tables and figures for the formatting purposes of the thesis.

Paper 3:

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

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Abstract

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, empirical evidence is limited. We examined the association of child survival with inter-annual variation in food crop yield and middle-upper arm circumference (MUAC) in a subsistence farming population of rural Burkina Faso. The study consisted of 44,616 children <5 years of age who were included in the Nouna Health and Demographic Surveillance System from 1992–2012, and whose survival was analysed 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 (fully adjusted hazard ratio of 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.

Keywords: agriculture, child mortality, climate change, edible grain, food, malnutrition, survival, undernutrition

Background

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 increases in the variability of weather and crop yields, as projected by climate change models (4).

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

A small number of studies have examined the link between proxies of crop yield variation and survival. For example, there are studies of the association between mortality and 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).

This paper examines the associations of child survival over the first five years of life, nutritional status as measured by middle-upper arm circumference (MUAC), and inter-annual food crop yield variation in a subsistence farming population in rural Burkina Faso, using large longitudinal datasets. Our main focus is on the associations of child survival with (i) variation in annual food crop yield in the year of child's birth and (ii) with MUAC. In addition, we examined whether MUAC (as an outcome) is associated with crop yield variation to explore if the association of child survival with crop yield is likely to operate through changes in nutrition (Figure 5–1).

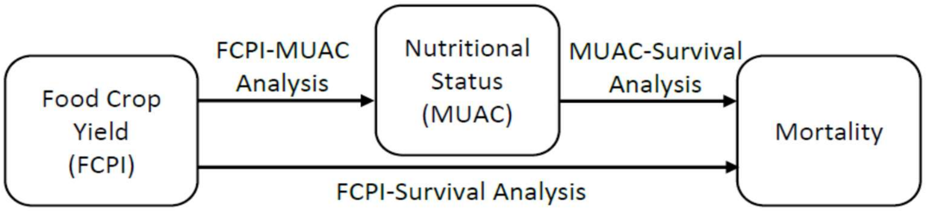

Figure 5—1. A conceptual map of the associations between food crop yield, nutritional status, and mortality examined in this paper.

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

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 of 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) consists almost exclusively of subsistence farmers relying on rain-fed agriculture, with their livelihoods being susceptible to variations in rainfall (12–14). We assembled the following data:

(1) Mortality/survival

The study of survival was based on data for 44,616 children less than 5 years of age who were included in the Nouna HDSS routine data collection for the period 1992–2012. During this period, the children were followed-up for vital events and migration every 3 months until 2006 and every 4 months thereafter. We obtained dates of birth and death or in-/out-migration. 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.

(2) MUAC

49,056 MUAC measurements were available (from the HDSS surveys) on 25,480 children <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 of January 2009 to December 2012 (i.e., overlapping with the period for which survival data were available). Values of MUAC greater than 5 standard deviations from the mean (i.e., outside the range of 67 to 218 mm) were deemed implausible and excluded from analysis (15–17).

(3) Agricultural yield data

Data on the annual yield (kg/ha) of each of the five 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:

$$\text{FCPI for year } i = \sum p_{ij} * w_{ij}$$

where

p_{ij} – yield in year i for crop j relative (percentage) to its mean yield over the period of 1992–2012

w_{ij} – proportion of the total harvest across the five 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 rice harvest proportion in 1994 was zero (a minor assumption since the period average rice harvest proportion was only 0.4%). Given similar food energy values 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).

(4) 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, drilled water wells, and the quality of road connection) 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 three separate analyses (Figure 5–1):

1) the association of survival (from birth to 5 years of age) with FCPI using data from 1992–2012,
2) the association of survival (to 5 years of age) with MUAC using data from 2009–2012, and
3) the association of MUAC with FCPI using data from 2009–2014.

The timeframe of each analysis was determined by data availability (see Supplementary Table 5–5 at the end of this chapter).

Child survival was examined by tabulation, Kaplan Meyer plots, and Cox proportional hazards models with shared frailty specified by village and with age as the analysis time. Observations of children lost to the 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 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 since birth till 5 years of age). Separate models were constructed with FCPI fitted (i) as a continuous numerical score (for convenience reported as the hazard ratio for a 90th to 10th centile decrease in FCPI – broadly reflecting a very good year *vs* a very bad year) and (ii) 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-variant exposure (thus allowing the incorporation of data for multiple MUAC measurements per child where available). Before being included in the Cox models, all MUAC values were standardised for season of measurement using a linear regression model.

Separate models were constructed with MUAC measurements fitted (i) as numerical scores (reporting results as the hazard ratio for a 90th to 10th centile decrease in MUAC) and (ii) as a three-value classifier (≤115, 115-, 125- mm).

For both sets (FCPI and MUAC) of survival analyses, 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, semi-rural (Nouna town) *vs* rural residence (villages), indicators of village infrastructural characteristics (presence of a market, health care facility, drilled water wells, and quality of road connection), a linear term for time trend (year), and a binary indicator of the existence of an undernutrition treatment programme. 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 because of potential influence on the precision of measurements.

The association between MUAC and 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 three time points. A model with FCPI exposure specified in the year of MUAC measurement (adjusted for the mean FCPI experienced since birth to measurement) was constructed to examine the effect of the most recent yield on MUAC, independently of yield exposures in the preceding years. A model with FCPI exposure specified in the year of birth (adjusted for the mean FCPI experienced between 1 and 5 years of age) was constructed to examine the effect of early life exposure to yield, independently of the subsequent exposures, on MUAC measured over children's lifetime till 5 years of age. A model with the exposure to lifetime average FCPI was constructed to examine the effect of all yields children experienced over their lifetimes till 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 cut-offs of 115 and 125 mm to detect severe and moderate acute undernutrition (22).

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

Table 5—1. Number of children, deaths, person-years, and mortality rate by individual characteristics, Nouna HDSS, Burkina Faso, 1992–2012 (n = 44,616 children <5 years of age.

Factors	No. of children	% of children	Deaths	P-y at risk[a]	Mortality rates per 1,000 p-y
Age					
0 – <1	44,616	100	2,069	40,305	51.33
1 – <2	37,040	83	1,295	33,171	39.04
2 – <3	30,939	69	757	27,700	27.33
3 – <4	26,246	59	272	23,625	11.51
4 – <5	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					
Sep–Nov	12,052	27	1,355	39,645	34.18
Dec–Feb	10,432	23	1,092	34,173	31.96
Mar–May	11,008	25	1,022	35,815	28.54
Jun–Aug	11,124	25	1,066	35,475	30.05
Season of exit from the follow up					
Sep–Nov	7,517	17	1,389	27,360	50.77
Dec–Feb	7,356	17	1,102	27,103	40.66
Mar–May	8,689	20	935	32,978	28.35
Jun–Aug	21,054	47	1,109	57,667	19.23

Abbreviations: HDSS, health and demographic surveillance system; P-y, person-years at risk

[a] Person-years at risk here are presented since birth till the end of the follow up.

Results

The characteristics of the study subjects monitored over the period of analysis for survival, 1992–2012, are given in Table 5–1 and Supplementary Table 5–6. 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.

The characteristics of the 16,698 subjects with MUAC measurements monitored over the period of analysis of 2009–2012 are presented in Supplementary Table 5–7. Mean MUAC among these subjects was 142 (95% confidence interval (CI): 141, 142) mm. 5% had MUAC ≤115 mm and 9% MUAC 115–125 mm. The earliest MUAC measurements were made in the first month of life with 43% made in the 1st and 21% between the 1st and 2nd years of life.

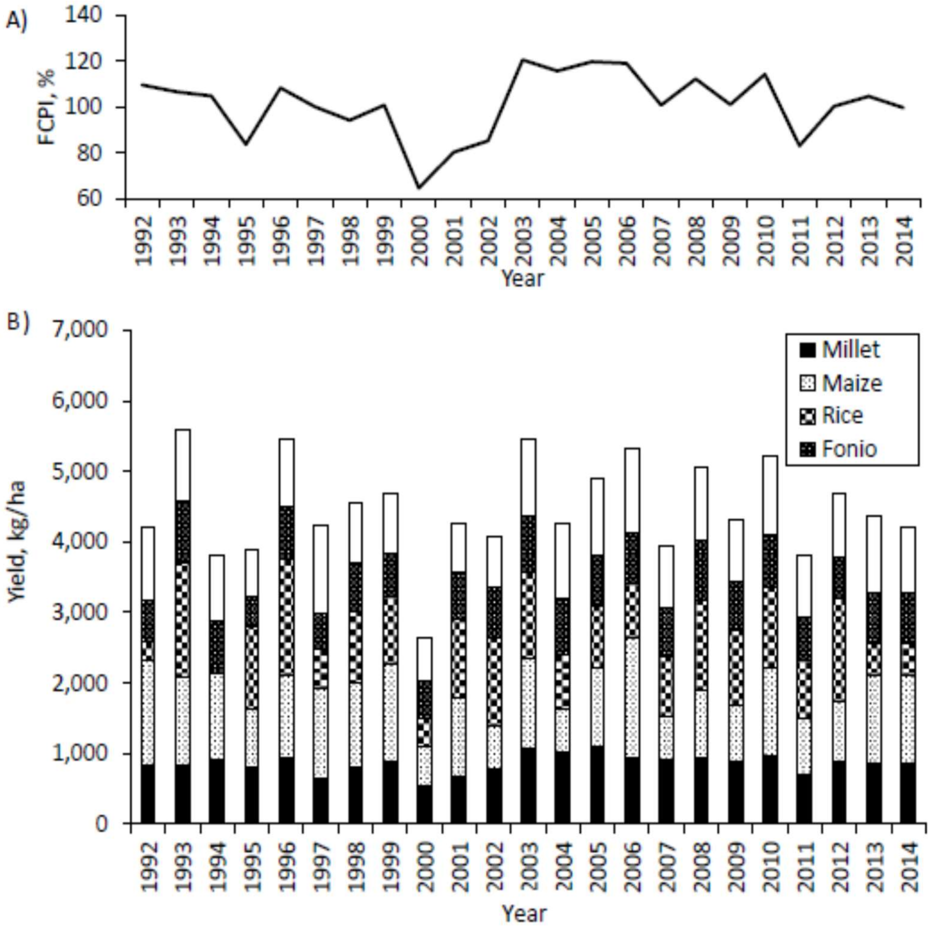

Figure 5—2. Time series of the FCPI (A) and annual yield of each individual crop comprising the FCPI (B) in the Kossi Province, Burkina Faso, 1992–2014.

Abbreviations: FCPI, food crop productivity index

Crop data showed the highest average yield (kg/ha) for maize, followed by rice, sorghum, and millet (Figure 5–2; Supplementary Table 5–8). Inter-annual variability in the FCPI was mainly driven by changes in the productivity of millet and sorghum, since on average millet and sorghum together constituted 89% of the total harvest of all the five food crops in the Kossi province (Supplementary Table 5–8). 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 the 10th–90th centile interval of 82%–119%.

Survival

K-M plots showed mortality risk to be highest in the first two to three years of age (Figures 5–3 and 5–4). Survival was lower among children born in years of below average FCPI than among children born in years of above average FCPI (Figure 5–3). Results of the Cox regression analyses showed that child survival was associated with FCPI in the year of birth (Table 5–2) 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.

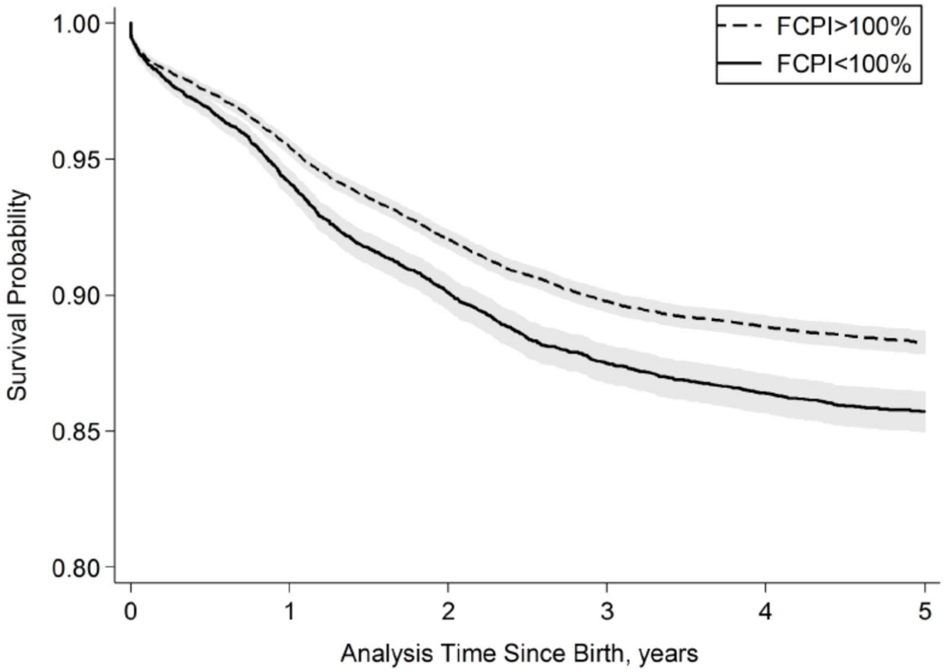

Figure 5—3. Kaplan-Meyer plot of survival probability among children <5 years of age in relation to the FCPI in the year of birth in Nouna HDSS, Burkina Faso, 1992–2012 (follow up starts on the date of birth, age is used as analysis time scale).

Abbreviations: CI, confidence interval; FCPI, food crop productivity index

Table 5—2. Results of Cox regression analysis: child survival to 5 years of age in relation to food crop yield in the year of birth in Nouna HDSS, Burkina Faso, 1992–2012 (n = 44,616 children).

Models[a] with different combinations of fixed effect adjustments and exposure specification	Hazard ratio for all-cause mortality	95% CI
Model 1[b]		
≥period mean FCPI[c]	1	Referent
<period mean FCPI	1.23	1.15, 1.31
Δ90–10p FCPI[d]	1.15	1.07, 1.23
Model 2[e]		
≥period mean FCPI[c]	1	Referent
<period mean FCPI	1.12	1.04, 1.20
Δ90–10p FCPI[d]	1.12	1.03, 1.21
Model 3[f]		
≥period mean FCPI[c]	1	Referent
<period mean FCPI	1.11	1.03, 1.18
Δ90–10p FCPI[d]	1.11	1.02, 1.20
Model 4[g]		
≥period mean FCPI[c]	1	Referent
<period mean FCPI	1.10	1.03, 1.18
Δ90–10p FCPI[d]	1.11	1.02, 1.20

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

[a] These are shared frailty 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. Models in relation to the continuous and categorical specification of the exposure were fitted separately (i.e., not mutually adjusted).

[b] Model 1 had no fixed effect adjustments.

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

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

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

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

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

Survival was also associated with MUAC measurements (Table 5–3; Figure 5–4). 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 model. For children with MUAC≤115 mm the hazard ratio was 2.73 (95% CI: 2.10, 3.55) and with MUAC 115–125 mm 1.94 (95% CI: 1.53, 2.48), compared to children with MUAC>125 mm. With the exclusion of children <6 months of age the hazard ratio for children with MUAC<115 mm, representing severe acute undernutrition, increased to 3.60 (95% CI: 2.30, 5.63) but did not change for children with MUAC 115–125 mm (Supplementary Table 5–9).

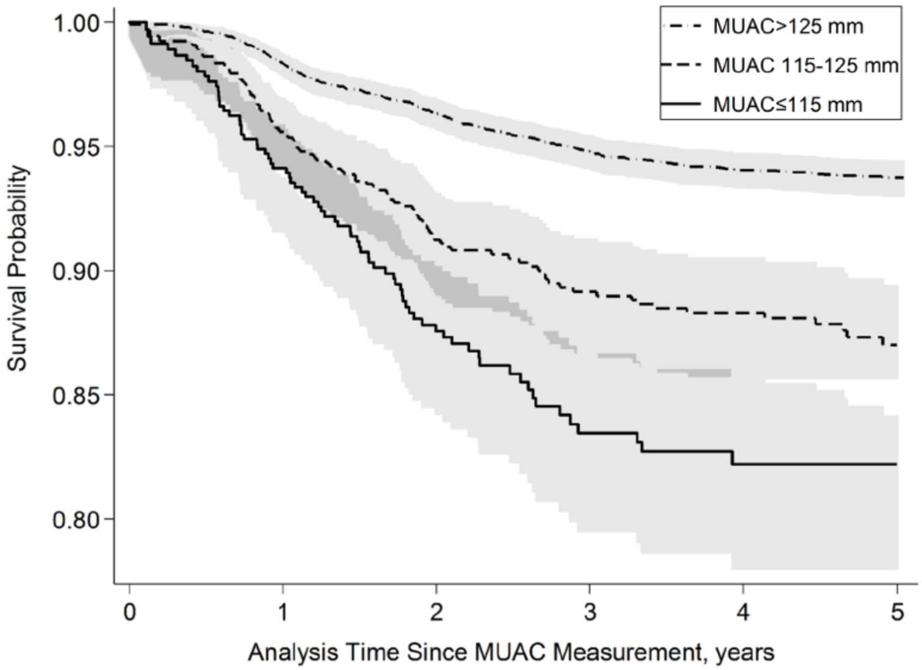

Figure 5—4. Kaplan-Meyer plot of survival probability among children <5 years of age in relation to the nutritional status, as measured by MUAC, in Nouna HDSS, Burkina Faso, 2009–2012 (follow up starts on the date of MUAC measurement, age is used as analysis time).

Abbreviations: CI, confidence interval; MUAC, middle-upper arm circumference

MUAC in relation to FCPI

The children's MUAC was also related to FCPI in the year of MUAC measurement and to lifetime average FCPI (Table 5–4), though not with the FCPI in the year of birth. In fully adjusted models, a decrease from 90th to 10th centile in FCPI in the year of measurement was associated with a decrease of 2.62 (95% CI: 2.08, 3.15) mm in MUAC, and the corresponding figure in relation to lifetime average FCPI was a decrease of 3.81 (95% CI: 2.89, 4.73) mm.

Table 5—3. Results of Cox regression analysis: child survival to 5 years of age in relation to the nutritional status, as measured by MUAC, in Nouna HDSS, Burkina Faso, 2009–2012 (n = 16,698 children, 18,511 MUAC measurements).

Models[a] with different sets of fixed effect adjustments and exposure specification	Hazard ratio for all-cause mortality	95% CI
Model 1[b]		
MUAC >125mm[c]	1	Referent
MUAC >115–≤125mm	2.10	1.65, 2.67
MUAC ≤115mm	3.05	2.36, 3.96
Δ90–10p MUAC[d]	3.04	2.42, 3.80
Model 2[e]		
MUAC >125mm[c]	1	Referent
MUAC >115–≤125mm	1.92	1.51, 2.44
MUAC ≤115mm	2.71	2.09, 3.52
Δ90–10p MUAC[d]	2.66	2.10, 3.36
Model 3[f]		
MUAC >125mm[c]	1	Referent
MUAC >115–≤125mm	1.94	1.52, 2.46
MUAC ≤115mm	2.73	2.10, 3.56
Δ90–10p MUAC[d]	2.70	2.13, 3.42
Model 4[g]		
MUAC >125mm[c]	1	Referent
MUAC >115–≤125mm	1.94	1.53, 2.48
MUAC ≤115mm	2.73	2.10, 3.55
Δ90–10p MUAC[d]	2.72	2.15, 3.44

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

[a] These are shared frailty 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. Models in relation to the continuous and categorical specification of the exposure were fitted separately (i.e., not mutually adjusted).

[b] Model 1 had no fixed effect adjustments.

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

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

[e] Model 2 was adjusted for presence of undernutrition treatment programme, time trend, MUAC measurement scale.

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

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

Table 5—4. Results of multilevel linear regression analysis: decrease in children's MUAC (mm) associated with a reduction in food crop yield in Nouna HDSS, Burkina Faso, 2009–2014 (n = 49,056 children <5 years of age).

Models[a] with different sets of fixed effect adjustments and exposure specification	*Decrease* in MUAC in mm with 90–10p decrease in FCPI	95% CI
Model 1[b]		
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[c]		
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[d]		
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[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	2.08, 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 presented models. Variables representing each timing of exposure to FCPI were fitted separately (i.e., there were three separate models for each set of confounder adjustment) to examine the influence of alternative measures of crop yield level at different times of children's lives.

[b] Model 1 had no fixed effect adjustments.

[c] Model 2 was adjusted for presence of undernutrition treatment programme, time trend, MUAC measurement scale, age and season at MUAC measurement, subsequent FCPI (used in models where FCPI in the year of birth was specified as the exposure) or preceding FCPI (used in models where FCPI in the year of MUAC measurement was specified as the exposure) or none of these two adjustments (in models where lifetime average FCPI was used as the exposure).

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

[e] Model 4, in addition to the adjustments of model 3, was adjusted for the presence of a market, health care facility, drilled wells, road quality, semi-rural *vs* rural residence.

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 a partial 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 previous published research. Such research includes a study which found positive association of childhood survival with spatial variability of food crop yield (approximated by mean Normalized 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 a positive association between wasting (an anthropometric measure used to determine the same type of undernutrition or 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 the availability of food 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 five years of age, which suggests that death is a persistent adverse consequence of reduced food availability around the time of, or shortly after, birth.

What our analyses do not clearly distinguish is whether this is most likely to be a consequence of *in utero* exposures to poor nutrition on the part of the mother leading up to birth, or of poor nutrition during the first year of life. Medical evidence demonstrates that both *in utero* and early life (first 24 months) undernutrition are 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 a higher chance of mental illness (29,30). Studies examining the health status of adult survivors who were exposed to historical famines *in utero* or early life in China, Russia, Finland, and the Netherlands observed poorer mental and physical health, manifested by impairments of the central nervous system, higher rates of coronary heart disease, metabolic dysfunction, and antisocial behaviour (31–38). Furthermore, a study of a Bangladeshi famine following monsoon flooding in 1974 found an increased mortality rate in the cohort of children born during the famine as compared to the cohorts conceived during or after the famine (39). These studies suggest higher frailty of those exposed to food shortages *in utero* and early life and a higher risk of mortality in subsequent life. Such individuals are suggested to 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, which in areas of rain-fed agriculture is often related to unfavourable 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 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, new-borns, 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, the use of drought resistant crops, the improvement of irrigation, improved health systems, and others.

Limitations

First, we acknowledge that because the hazard ratios for survival in relation to FCPI are not large, there is a 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 (FCPI) in our study population of Nouna HDSS which covers around one third of the province. Despite this approximation, we found strong associations between the relative yield measure and nutritional and mortality outcomes among children <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 centre and context exploration. We identified the establishment of the undernutrition treatment programme 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 identified here.

An even stronger associations of survival with MUAC and MUAC with FCPI could be observed if MUAC measurements in our dataset 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. But it might also reflect a bias that fewer children with low MUAC 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, the mean MUAC was 126 (95% CI: 123, 129) in those who died before 12 months and 135 (95% CI: 134, 136) in those who survived to 12 months, and mortality rates of 30 *vs* 27 deaths per 1,000 person in children born in years with below and above average FCPI respectively.

The analysed data series were sufficient to examine each association of our 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 <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. The children’s MUAC was also associated with the relative yield of the preceding harvest and the average yield over the children’s lifetimes.

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

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Supplementary Material

Table 5—5. Structure of the Nouna HDSS datasets used for analyses and their temporal overlap.

Calendar year	Observations	
	Births	MUAC measurements
1992	603	
1993	731	
1994	771	
1995	1,328	
1996	1,207	
1997	1,968	
1998	2,200	
1999	2,757	
2000	3,232	
2001	3,139	
2002	3,051	
2003	3,408	
2004	3,345	
2005	3,383	
2006	3,436	
2007	3,733	
2008	3,698	
2009	3,398	10,372
2010	3,716	1,254
2011	3,580	2,120
2012	3,339	4,946
2013		15,857
2014		14,507

FCPI—survival analysis

MUAC—survival analysis

FCPI—MUAC analysis

Abbreviations: FCPI, food crop productivity index; MUAC, middle-upper arm circumference

Table 5—6. Number of villages, child deaths, person-years, and mortality rate by village characteristics, Nouna HDSS, Burkina Faso, 1992–2012 (n = 59 villages with 44,616 children <5 years of age).

Factors	No. of villages	% of villages	Deaths	P-y at risk[a]	Mortality rates per 1,000 p-y
Villages *vs* Nouna					
villages	58	98	3,980	118,659	33.54
Nouna	1	2	555	26,448	20.98
Market					
absent	37	63	1,515	43,525	34.81
present	22	37	3,020	101,582	29.73
Road quality					
limited	20	34	1,510	37,953	39.79
average	29	49	1,989	61,012	32.6
permanent	10	17	1,036	46,143	22.45
Healthcare facilities					
absent	45	76	2,188	63,026	34.72
present	14	24	2,347	82,082	28.59
Drilled wells					
absent	40	68	1,981	60,176	32.92
present	19	32	2,554	84,932	30.07

Abbreviations: HDSS, health and demographic surveillance system; P-y, person-years at risk

[a] Person-years at risk here are presented since birth till the end of the follow up

Table 5—7. Number of MUAC measurements, deaths, person-years, and mortality rate by selected individual characteristics, Nouna HDSS, Burkina Faso, 2009–2012 (n = 18,511 measurements, 16,698 children <5 years of age).

Factors	No. of measurements	% of measurements	Deaths	P-y at risk[a]	Mortality rates per 1,000 p-y
MUAC					
>125mm	16,043	87	320	26,399	12.12
>115–≤125mm	1,620	9	89	2,824	31.51
≤115mm	848	5	75	1,459	51.39
Age at measurement					
0 –	7,887	43	332	14,694	22.59
1 –	3,818	21	103	7,259	14.19
2 –	3,091	17	39	5,108	7.63
3 –	2,085	11	8	2,779	2.88
4 –	1,630	9	2	842	2.38
Sex					
male	9,300	50	260	15,507	16.77
female	9,211	50	224	15,176	14.76
Season of measurement					
Sep–Nov	3,158	17	64	2,939	21.77
Dec–Feb	3,182	17	39	2,599	15.00
Mar–May	10,573	57	333	22,527	14.78
Jun–Aug	1,598	9	48	2,617	18.34
Season of birth					
Sep–Nov	5,126	28	151	8,664	17.43
Dec–Feb	4,316	23	135	7,615	17.73
Mar–May	4,528	24	97	7,115	13.63
Jun–Aug	4,541	25	101	7,289	13.86
Season of exit from the follow up					
Sep–Nov	2,364	13	167	4,858	34.37
Dec–Feb	11,257	61	93	16,561	5.62
Mar–May	2,623	14	84	5,014	16.75
Jun–Aug	2,267	12	140	4,249	32.95

Abbreviations: HDSS, health and demographic surveillance system; MUAC, middle-upper arm circumference; P-y, person-years at risk

[a] Person-years at risk here are presented since MUAC measurement till the end of the follow up

Table 5—8. Characteristics of crop production variability in the Kossi province, 1992–2014.

Characteristics	Mean	Median	5th, 95th centile
Crop yield (kg/ha)			
Millet	859	879	636, 1,066
Sorghum	945	934	681, 1,208
Maize	1,067	1,171	598, 1,469
Fonio	683	706	522, 831
Rice	964	983	418, 1,620
Proportion of the crop-specific harvest (%)[a]			
Millet	55	54	36, 71
Sorghum	34	36	18, 46
Maize	6	5	2, 13
Fonio	5	4	3, 6
Rice	0.4	0.3	0.04, 1.2
FCPI (%)	100	100	80, 119

Abbreviations: FCPI, food crop productivity index

[a] Summary statistics are presented for the annual crop-specific harvest proportion of the total harvest of the five food crops, expressed in per cent terms

Table 5—9. Results of sensitivity analysis of the Cox regression: child survival from 6 months to 5 years of age in relation to their nutritional status, as measured by MUAC, Nouna HDSS, Burkina Faso, 2009–2012 (n = 12,390 children aged 6 months–5 years).

Models[a] with different sets of fixed effect adjustments and exposure specification	Hazard ratio for all-cause mortality	95% CI
Model 1[b]		
MUAC >125mm[c]	1	Referent
MUAC >115–≤125mm	1.91	1.31, 2.79
MUAC ≤115mm	3.60	2.32, 5.60
Δ90–10p[d] MUAC	2.45	1.71, 3.51
Model 2[e]		
MUAC >125mm[c]	1	Referent
MUAC >115–≤125mm	1.84	1.26, 2.68
MUAC ≤115mm	3.35	2.14, 5.22
Δ90–10p[d] MUAC	2.26	1.57, 3.26
Model 3[f]		
MUAC >125mm[c]	1	Referent
MUAC >115–≤125mm	1.84	1.26, 2.68
MUAC ≤115mm	3.50	2.23, 5.48
Δ90–10p[d] MUAC	2.30	1.59, 3.33
Model 4[g]		
MUAC >125mm[c]	1	Referent
MUAC >115–≤125mm	1.91	1.30, 2.79
MUAC ≤115mm	3.60	2.30, 5.63
Δ90–10p[d] MUAC	2.36	1.63, 3.41

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

[a] These are shared frailty 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 has no fixed effect adjustments.

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

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

[e] Model 2 was adjusted for presence of undernutrition treatment programme, time trend, MUAC measurement scale.

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

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

5.2. Commentary on Paper 3 *Annual crop yield, survival and nutrition*

The principal findings of this chapter (published in Belesova et al. *AJE*, 187(2):242–250, 2018) were that changes in annual provincial crop yield were associated with annual changes in child MUAC and with survival, and that children's MUAC was associated with survival. These finding suggested that children's chances of survival were appreciably worse if the child was born in a year of low crop yield.

A number of methodological issues relevant to this paper are worthy of comment in relation to this thesis.

(i) Year-to-year variation

These analyses were based on *year-to-year* variation of crop yield at the province level related to the outcomes of interest (child survival and MUAC). Hence, the analyses directly addressed the aim of this thesis, which was to examine annual crop yield variation as an epidemiological risk factor. Temporal (*year-to-year*) crop yield variation (as opposed to spatial variation) is pertinent to the context of weather variability and climate change, as weather variability and its associated crop yield variation may change over time due to climate change.

(ii) Limited account of extreme crop yield deficit

The estimates of the effect of crop yield variation on child survival and MUAC were derived assuming a linear association. This assumption did not permit the exploration of possible differences in the magnitude of effect between more *vs* less extreme annual yield reductions. For example, it is possible that the relatively extreme yield deficit in the year of 2000 could be associated with higher effect estimates than the estimates presented in the paper. The possibility of such differences could be discerned if the analyses were based on non-linear statistical modelling (as in Chapter 4). However, here statistical power to determine the shape of the function was limited (there were only 21 annual provincial crop yield data points available for this analysis).

Furthermore, linear associations could not determine whether there is a level of crop yield that is no longer associated with additional risk for child survival or a decrease in MUAC, i.e., a level of crop yield which could suffice for the needs of the local population without posing an additional risk for these outcomes. The effect estimates are presented for a change in FCPI from 90th to 10th centile and as a risk ratio for FCPI below *vs* above its period average value. Yet, it remains uncertain whether these intervals include a yield level that would pose no harm for the examined outcomes.

(iii) Control for confounding

I used several adjustments to minimise the likelihood of alternative explanations for the differences in the annual outcome (survival and MUAC) level. Analyses were based on a comparison of survival/MUAC in one birth cohort against survival/MUAC in another birth cohort by village (specified as shared frailty by village in survival analyses and as village-level random effects in the analyses of MUAC in relation to annual yield). Additionally, I adjusted the analyses for various individual and village characteristics. These adjustments did not notably change the results of the analyses (see Table 5–2, 5–3, 5–4), suggesting that they had a low potential for introducing confounding. However, adjustments for village characteristics were based on the assumption that these did not vary over time, as the adjustment variables were based on data collected at one point of time. Hence, analyses were not controlled for their variation over time. The analyses were adjusted for time trend to control for any linear changes over time and for the establishment of the undernutrition treatment programme. There could potentially be other factors that changed over time non-linearly and were associated with both – provincial annual crop yield variation and changes in birth cohort survival. Further control for any unknown effects at the year level by specifying shared frailty by year was not possible, as it requires at least several exposure values in each year. As in each year I had available only one yield measure for the entire study area (i.e., province-level yield values), such adjustment in this study was not possible.

(iv) Other sources of bias

It may be possible that households adjust their family planning and migration behaviours in response to annual crop yield variations. Such behaviours might influence the proportion of vulnerable children present in the Nouna HDSS population on an annual basis in such a manner that it may correlate with annual crop yield variation. Similarly, in analyses of MUAC in relation to annual crop yield variation in the year of birth, the proportion of vulnerable children surviving until the time of their MUAC measurement may correlate with the level of yield in their year of birth. The design of my analyses did not eliminate the possibility of bias related to selective migration and fertility as well as the possibility of survival bias, all of which remain a limitation of the study. However, it is uncertain whether any selective migration and fertility or survival bias were actually present in this setting.

(v) Exposure classification

The association of annual crop yield variation with child survival was examined considering only the exposure to crop yield in the year of birth. The effect of this exposure was examined independently, controlling for the yield level experienced in subsequent years of life. These analyses did not examine the cumulative survival effects of yield experienced in each year of life, which would require more sophisticated analyses and possibly longer data series.

Analyses of the association of annual crop yield with MUAC explored the possibility of the effect of exposure to yield variation at three different (mutually controlled) timings: year of birth, lifetime average, and the year of MUAC measurement. The magnitude of the effect estimate in relation to the lifetime average exposure was higher than the magnitude of effect estimated in relation to the exposure in the year of MUAC measurement. This may suggest value in further research into the effect of lifetime cumulative exposure to crop yield.

5.3. Consistency with other evidence

The direction of the association of child survival with crop yield variation identified in this chapter is consistent with the direction of similar associations identified in other studies: (1) the association suggesting a protective effect on the part of a monthly household food security measure, which was based on *year-to-year* variation in rice and maize yield for the same-month child mortality in Tanzania [99], and (2) the association of child survival with NDVI (approximating spatial yield variation) in the year of birth in Mali and Burkina Faso [94]. The plausibility of the identified association was further supported by analogous associations of child mortality with annual rainfall, approximating drought conditions, in rural Burkina Faso [107] and India [138], as well as seasonal differences in food availability in Gambia [139,140]. Yet, further studies providing consistent results are needed to strengthen the evidence of the effect of low annual crop yield on an increased risk of child mortality.

The direction of the association of annual crop yield variation with MUAC was consistent with the direction of the associations of wasting (measured by weight-for-height index) identified in other studies with the same year NDVI in Nepal [96,97], and NDVI in the year of birth in Mali [94]. Furthermore, analogous associations were identified for child anaemia with temporal changes in food prices in Indonesia [141], with drought at the time of birth in India [138], and with monthly and annual rainfall deviations from their long-term means in Burkina Faso [78]. Some studies also looked at the associations of NDVI with the height-for-age index, but suggested inconclusive results concerning the presence of this association across settings [91–94,96–98]. However, results in relation to the height-for-age index are less comparable to my results, as height-for-age reflects long-term as opposed to short-term changes in nutrition, which are reflected by MUAC. Further studies examining the association of child MUAC with annual crop yield variation are necessary for further contribution to the weight of evidence for this association.

5.4. Possible mechanisms of effect

If the identified association of crop yield variation with child survival is causal, the underlying mechanism of effect may have several possible explanations. It could be explained by reduced food availability and intake by children, with subsequently higher risk of undernutrition, infectious diseases, and eventually an increased risk of mortality [12]. This may also be an effect of exposure *in utero* to poor nutrition of the mothers leading up to birth, with a subsequently increased risk of low birth weight in children, and the related increase in the risk of child morbidity and mortality [142,143]. Yet, the extent to which the effect of yield variation on survival is related to *in utero* exposure *vs* exposure in the first year of life remains unclear. The effects of reduced crop yield could also operate through reduced household income from food crop sales which may limit even the most essential day to day expenses, including health care expenses, subsequently reducing households' ability to cope with any health risks that require medical treatment [144].

Findings concerning the association of crop yield variation with MUAC and the association of child survival with MUAC (which is well recognized in the literature [21,80]) suggested that in the Nouna HDSS nutritional status is likely to mediate the association of child survival with crop yield variation at least in part. Yet, the extent to which the association could be mediated by this mechanism as opposed to any other possible mechanisms that do not function through nutritional changes is unclear and requires formal mediation analyses which were not possible on the available Nouna HDSS data due to insufficient temporal overlap of the datasets. To further determine the relevance of the association of annual crop yield variation with child survival to undernutrition, I considered performing similar survival analyses in relation to undernutrition-related (as opposed to all-cause) mortality. The Nouna HDSS collects data on the cause of death using the verbal autopsy method, where the cause is determined based on signs and symptoms reported by members of the household of the deceased individual in response to a structured HDSS questionnaire [7,145]. However, the number of deaths with the recorded cause of undernutrition in Nouna HDSS data was too low to permit such an analysis [145]. Therefore, I did not pursue survival analyses of undernutrition-specific mortality in relation to annual crop yield variation.

Similarly, this study did not determine whether and to what extent the mechanism operating through nutritional changes is mediated by changes in the direct consumption of subsistence produce as opposed to changes in household income from crop sales, food expenditure, and the consumption of purchased food items. Therefore, further investigation into the causal mechanisms of this association and their relative importance is required.

5.5. Implications of Paper 3 *Annual crop yield, survival and nutrition*

In contrast to the previous chapter, where the association of child MUAC was examined in relation to harvest differences across households, this chapter provided direct evidence of the association of child MUAC and survival with annual changes in crop yield. Therefore, it is important to highlight the implications of this chapter's findings for annual crop yield variation as a risk factor for child undernutrition and mortality in the Nouna HDSS and to consider them in relation to the indirect evidence provided in the previous chapter.

If the identified associations are causal, they suggest that children in the Nouna HDSS born in a year of low crop yield have on average a lower chance to survive till the age of 5 years and in years of lower yield children on average have poorer nutritional status. Therefore, low annual crop yield appears to be a likely epidemiological risk factor for child undernutrition and mortality in this area.

Unlike the findings of Chapter 4, which remained subject to potential uncontrolled confounding by socio-economic factors, the findings of this chapter are less likely cofounded by such factors. Although some residual confounding by temporally varying factors could still have been possible, this chapter provided stronger evidence for the association of annual crop yield with child MUAC and survival in the Nouna HDSS population.

The nature of the effect of harvest differences across households on child MUAC in a single year (Chapter 4) may be different from the effect of inter-annual differences in crop yield variation (Chapter 5). The former concerns the risk households experience in relation to their own crop production, whilst the latter concerns changes in the risk to the population in relation to crop yield changes from one year to another. Taken together, their evidence suggests that with annual deficits in crop yield, relative to an average year, there are likely to be more households in the Nouna HDSS area harvesting an insufficient level of crop harvest for their needs, and possibly experiencing an increased risk of acute child undernutrition and mortality. However, the dependence of child MUAC on household crop harvest may vary from year to year depending on whether it is a year of good harvest. Further research is needed to explore the temporal variation in such risk.

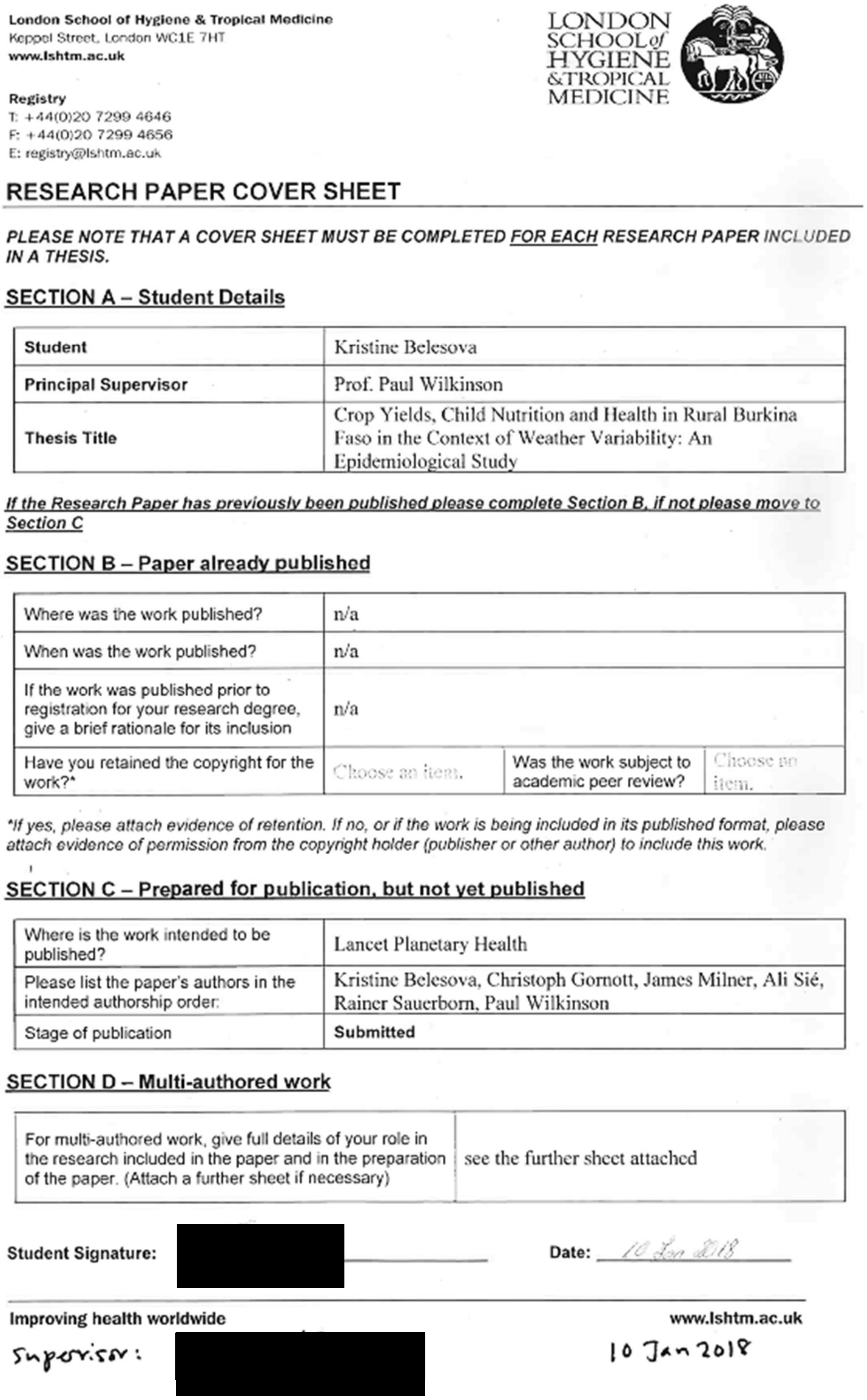
This chapter contributed evidence of the change in the risk of child mortality and nutritional status associated with annual crop yield variation. If the identified associations are causal, they will suggest that an annual crop yield deficit poses an additional risk of child mortality and undernutrition in the Nouna HDSS population. The findings in this chapter had a limited capacity to determine the effects of extreme yield deficit and any counterfactual level of yield which may no longer be associated with additional risk. Furthermore, these analyses did not address the drivers of annual crop yield variation, requiring further investigation into the fraction of the risk that is associated with the weather-related part of the variation. Given a high level of reliance of this population on rain-fed agriculture, these risks could be in part attributed to weather-related crop yield variations and may fluctuate due to climate change.

In the next chapter I will estimate the burden of child mortality that could be attributed to the recent annual crop yield variations in the Nouna HDSS area. I also will identify the proportion of this attributable burden that could be specifically caused by weather-related yield reductions and suggest possible changes to this impact under weather conditions projected for the most conservative future climate change trajectory.

Chapter 6: The mortality impact of low annual crop yields in the context of weather variability

The previous chapter identified an empirical relationship between child survival and annual crop yield in the year of birth. This chapter presents estimates of the burden of child mortality attributable to low crop yields in the Nouna HDSS population now and under a future climate change trajectory modelled using this empirical relationship. This modelling entails the use of: (i) a quantitative analysis of the link between weather parameters and crop yields, based on statistical crop models co-developed with my research collaborators, so as to estimate the degree to which annual crop variations are attributable to variations in weather during the crop growing season; and (ii) data derived from general circulation models which project future weather conditions under the conservative trajectory of 1.5 °C global warming by the end of the 21st century.

6.1. Paper 4 *The mortality burden of low crop yields in the context of current and future climates*



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RESEARCH PAPER COVER SHEET

PLEASE NOTE THAT A COVER SHEET MUST BE COMPLETED FOR EACH RESEARCH PAPER INCLUDED IN A THESIS.

SECTION A – Student Details

Student	Kristine Belesova
Principal Supervisor	Prof. Paul Wilkinson
Thesis Title	Crop Yields, Child Nutrition and Health in Rural Burkina Faso in the Context of Weather Variability: An Epidemiological Study

If the Research Paper has previously been published please complete Section B, if not please move to Section C

SECTION B – Paper already published

Where was the work published?	n/a		
When was the work published?	n/a		
If the work was published prior to registration for your research degree, give a brief rationale for its inclusion	n/a		
Have you retained the copyright for the work?*	Choose an item.	Was the work subject to academic peer review?	Choose an item.

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SECTION C – Prepared for publication, but not yet published

Where is the work intended to be published?	Lancet Planetary Health
Please list the paper's authors in the intended authorship order:	Kristine Belesova, Christoph Gornott, James Milner, Ali Sié, Rainer Sauerborn, Paul Wilkinson
Stage of publication	**Submitted**

SECTION D – Multi-authored work

For multi-authored work, give full details of your role in the research included in the paper and in the preparation of the paper. (Attach a further sheet if necessary)	see the further sheet attached

Student Signature: [redacted] **Date:** 10 Jan 2018

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Supervisor: [redacted] 10 Jan 2018

Section D – Multi-authored work

I conceived the idea and led the design of the study with advisory input from Prof. Paul Wilkinson, Prof. Rainer Sauerborn, and Mr. Christoph Gornott. I obtained data on crop yield production and parameters required for the modelling of yields in relation to weather variations. Mr. Christoph Gornott used these data as inputs to calibrate his previously developed statistical models of weather effect on crop yields for the area of the Kossi province. I suggested the addition of certain variable specifications to these models in order to enhance their appropriateness for the study location and thesis objectives. Therefore, the final structure of the crop models was agreed between Mr. Christoph Gornott, Prof. Paul Wilkinson, and myself through joint discussions. Mr. Christoph Gornott helped obtaining future weather projection data from the ISI-MIP team. I used output of the crop models, i.e., weather-attributed part of crop-specific yield variation and crop-specific yield projections under climate change, to independently construct the exposure indices of crop yield variation across crop types. I independently developed models of the impact of crop yield variation on child mortality with advisory input from Dr. James Milner and Prof. Paul Wilkinson. Dr. James Milner also reviewed the correctness of these models. I independently performed monetary calculations with advisory input from Mr. Paul Drummond, Dr. Paolo Agnolucci, and Prof. Paul Ekins. I produced the first draft of the paper, edited it in response to all co-authors' comments, and prepared it for submission to *The Lancet Planetary Health*.

Student signature: Belesova 10 Jan 2018

Supervisor signature: 10 Jan 2018

Paper 4:

Mortality Impact of Low Annual Crop Yields in Rural Burkina Faso in the Context of Current and Future Climates

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Short title: The mortality burden of low crop yields in the context of current and future climates

Status: Under review in *Lancet Planetary Health*

Abstract

Background

In the subsistence farming populations of Burkina Faso, years of low crop yields result in poorer child nutrition and survival. Moreover, low yield years are projected to be more frequent under future climate. We developed models to quantify the associated health impacts now and under 1·5 °C of global warming by 2100.

Methods

We used life-tables based on age-specific mortality rates from the Nouna Health and Demographic Surveillance System to model the impact of low crop yields on mortality using published evidence for the relationship between crop yields and child (<5 years) survival. Statistical crop models were used to quantify the impacts in relation to weather, observed and projected, under 1·5 °C warming trajectory.

Findings

In eight years over the period of 1984–2012, annual crop yields were <90% of the period average, resulting in a food production deficit equivalent to 178 kilocalories/adult equivalent/day when averaged over the whole period. This deficit was estimated to contribute 7 child deaths (<5 years) or 438 years of life lost annually per 100 thousand people (all ages), 72% of which is attributable to the effect of weather on crop yields. Assuming all other factors remain unchanged, this burden would increase about two times if global warming of 1·5 °C were to occur by 2100.

Interpretation

Low crop yields in this population are largely attributable to weather factors and have an appreciable impact on child survival. Such evidence strengthens the case for action to mitigate climate change and for adaptation efforts to help protect children against the adverse effects of low crop yields.

Keywords: crop yield, food security, years of life lost, mortality, climate change, weather variability, child undernutrition, interventions, mitigation, adaptation

Research in context

Evidence before this study

- We searched the Medline and Google Scholar databases in September 2016 using the search terms (“mortality” OR “survival” OR “deaths” OR “malnutrition” OR “undernutrition” OR “nutrition”) AND (“yield” OR “harvest” OR “grain” OR “agricultural production” OR “drought”) AND (“child” OR “children”). We identified three systematic reviews and cross-checked their references.
- We could not identify any studies estimating the burden of child mortality attributable directly to annual crop yield variation.
- A small number of studies examined the associations between mortality and proxies of crop yield.
- Two studies provided global modelling estimates of future levels of child undernutrition under different scenarios of climate change impact on food availability. None of these studies were based on direct empirical evidence of the relationship between weather variation, food production, nutrition, and child mortality. These presented global and regional averages, which may not represent the magnitude of impact in the most vulnerable populations, such as subsistence farmers.

Added value of this study

- This study is the first attempt to combine evidence from climate modelling, statistical analysis of crop yields, and epidemiology to estimate the child mortality impacts of low crop yields in a subsistence farming population of sub-Saharan Africa.
- It suggests appreciable adverse impacts on child mortality from crop deficits in many years.
- Assuming other factors remain constant, the mortality burden attributable to low crop yields is estimated to increase around two-fold in the case of 1·5 °C of global warming by 2100.

Implications of all the available evidence

- The evidence further strengthens the case for addressing the impacts of low crop yields and weather variations to protect child health, which might be achieved at a relatively low cost.

Introduction

Studies from Ethiopia,[1] Mali,[2,3] and Burkina Faso[4] suggest that poor harvests are an important risk factor for child nutrition and health in subsistence farming populations of sub-Saharan Africa. Furthermore, low crop yields in the year of birth are associated with poorer child survival.[3,4] To date, however, there have been few attempts to quantify the health burden of the *year-to-year* variation in crop yields or of specific crop failures and to estimate the possible future health burden which might arise due to climate change.

Annual variations in crop yields occur for a variety of reasons, but in areas with rain-fed agriculture, the principal cause is weather variation, especially that of precipitation and temperature patterns during the growing season.[5] Moreover, there is concern that climate change may increase the frequency and severity of yield losses.[6] Modelling by Nelson *et al* has suggested that climate change-related yield decline may increase the number of underweight children worldwide by 24% by 2050,[7] while Lloyd *et al* suggested that climate change may result in an additional 45% relative increase in child stunting in West Africa by the same year.[8] However, neither of these studies was based on direct empirical analyses of the relationship between weather variations, food production, nutrition, and health outcomes. A few empirical studies have associated precipitation (including anomalies) or variation in the Normalized Difference Vegetation Index (NDVI) with child nutrition and survival.[1–3,9,10] However, these studies do not enable it to be clearly determined as to whether these associations operate specifically through weather-related variation in agricultural yields.

In this paper, we aim to help inform policy by developing models to quantify the impact of low crop yields on mortality in a subsistence farming population of Burkina Faso and to attribute such impacts to unfavourable growing-season weather conditions (including temperature extremes, dry spells, average precipitation, and others) during recent years and under a future climate change trajectory.

Methods

The study was based on empirical evidence derived from longitudinal analyses of over 20 years of child survival and agricultural data[4] from the Nouna Health and Demographic Surveillance System (HDSS) in Kossi province, North West Burkina Faso. This area is classified as dry orchard savannah with annual average precipitation of 796 mm over the past five decades.[11] The Nouna HDSS system covers nearly a third of the area of the province. By 2010 it covered 59 villages with a population of 89 thousand.[12] This population has been monitored by the Centre de Recherche en Santé de Nouna (CRSN) since 1992 till this date, through regular surveys of demographic, socio-economic, and health data. The single agricultural production season in this area covers the rainy season of June to October (see Annex 4 for further details).[13] The population relies almost exclusively on subsistence farming based on rain-fed agriculture.[13] Irrigation has been implemented in only 2·1 km^2 of the 7,328 km^2 of the total area of the province.[13]

To assess the mortality impacts of both crop variations and weather-related crop variations on this population, we developed and applied two sets of models (Figure 6–1):

(1) Model of the impact of low crop yields on mortality

The model of mortality impact was based on a life table[14] constructed for the Nouna population using age and sex-specific mortality data from the Nouna HDSS, averaged over the period of the availability of this data from 1992–2012. Relative risks for mortality in children <5 years were applied to this life table using year-specific estimates corresponding to the annual crop yield deficit. Specifically, using evidence from a published epidemiological study for the same population,[4] the relative risk of mortality in a given year was assumed to apply to the cohort of children born in that year and to their mortality risk in each subsequent year until the age of 5 years, but not at older ages.

The measure of crop yield used was the annual Food Crop Productivity Index (FCPI)[4] which reflects the total yield of the main cereal food crops (millet, sorghum, maize, fonio, rice) for that year relative to the annual mean yield for the period of 1992–2012 (selected for consistency with the period used to define FCPI in the derivation of the exposure–response function[4]). Thus, an FCPI of 80% represents a 20%

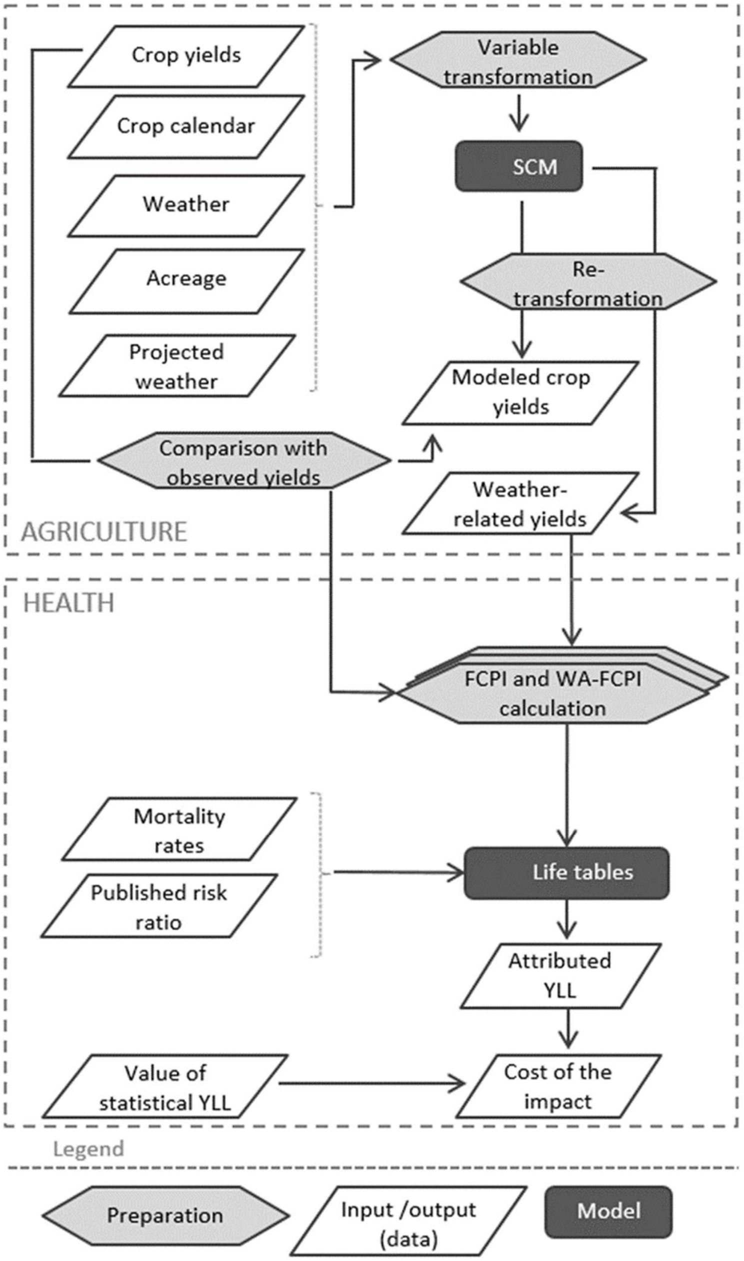

Figure 6—1. Flowchart of weather-agriculture-health modelling approach.

To develop estimates of child mortality attributable to low crop yields under the current and future climates we combined agricultural models of weather effects on crop yields (components: observed crop yield and acreage data, observed and projected weather data, crop calendar) with health modelling of child mortality impact of low crop yield (components: age- and sex-specific mortality rates, published risk ratio of child mortality impact of low crop yields,[4] the value of statistical life and economic parameters).

Abbreviations: FCPI, Food crop productivity Index; SCM, Statistical Crop Model, WA-FCPI, Weather-Attributed Food Crop Productivity Index; YLL, Years of Life Lost.

reduction in overall food crop yield in Kossi province relative to the period average. Algebraically, for year i, the FCPI was calculated as the sum of crop-specific relative yields with each crop weighted by its proportion of the total crop harvest:

$$FCPI_i = \sum_{j}^{J} y_{ij} * w_{ij}$$

$FCPI_i$ – relative food crop yield (%) for year i

y_{ij} – yield in year i of crop j relative to its mean yield in 1992–2012

w_{ij} – harvest of crop j in year i as a proportion of the total harvest across the five food crops

j – identifier of each food crop (millet, sorghum, maize, fonio (a form of millet), rice) with j=1,… , J

We obtained provincial data for Nouna on annual harvests (kg), acreage (ha), and yields (kg/ha) for each of the five food crops from national annual agricultural surveys supplied by the Agricultural Statistics Service of Burkina Faso for the period of 1984–2012.

(2) Models of crop yield in relation to growing season weather parameters

In order to estimate the impact of weather on annual crop yields in Kossi province, we developed crop yield models for each of the five main cereal crops using an adaptation of the conceptual framework of Gornott and Wechsung[15] (see Annex 4 for further details). These models entailed the regression of crop-specific annual yield data for the province over the period of 1984–2012 on growing season weather data derived from WFDEI (Water and Global Change Forcing Data Methodology Applied to the European Centre for Medium-Range Weather Forecasts Interim Re-Analysis).[16,17]

The following growing season variables were tested and retained in the model if they contributed to the goodness of fit (adjusted R^2): total solar radiation, total precipitation, mean vapour pressure deficit, growing degree days (optimum temperature for crop growth of 8–30 °C), killing degree days (temperature >30 °C), days without precipitation, dry spells longer than 5 days, and heavy precipitation events (>40 mm per day) (detailed definitions of each variable available in Annex 4). In addition, total acreage under cultivation was included to capture inter-annual changes in agricultural management, as its changes are often collinear with farmers' responses to changes in soil quality (e.g., acreage expansion with lower soil productivity) and availability of labour for field cultivation (e.g., insufficient labour availability could limit expansion of acreage).[18]

Using this model, for each year of the analysis period we determined the weather-attributable variation in each of the five main crop types[19] and hence, the contribution of weather factors to the annual yield deficit.

To examine how crop yields might vary under a future climate change trajectory, we applied the regression coefficients from the crop models to weather data derived from two general circulation model (GCM) realisations (see details in Annex 4). These GCM realisations correspond to a conservative assumption of a global mean temperature increase of 1·5 °C above pre-industrial levels by the end of the century,[20] the aspirational target agreed at the 2015 Paris conference of the United Nations Framework Convention on Climate Change (UNFCCC). Although based on conservative assumptions of climate change, these GCM data were chosen as the best available projections from the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP2b) – an international climate-impact modelling network.[20]

Projections of future crop yields were derived from these data assuming no change in non-climate parameters and were summarised for 30 year periods centred on 2015, 2050, and 2100 (see Annex 4 for further details).

Analyses

Using the mortality and the crop yield models, we computed the attributable child (<5 years) mortality impact for an average and maximum year of:

a. Observed crop yield deficit over the period 1984–2012;

b. Weather-related crop yield deficit over the period 1984–2012;

c. Theoretical crop yield deficit under the weather projections of 1·5 °C global warming trajectory, assuming all other factors remain unchanged.

In these three analyses, we assumed there would be a negative effect on survival (with respect to 100% of the average of the period from 1992–2012) only when crop yields (observed or modelled) were below 90% of the period average.

For each impact estimate, the primary outcomes were years of life lost (YLL) and deaths of children less than 5 years of age. We translated the estimated YLL into a monetary equivalent (2011 US dollars (USD) at purchasing power parity (PPP) corrected rates) using a welfare-based approach of estimating impact cost based on people's Willingness-To-Pay (WTP) for a reduction in the risk of mortality.[21] As WTP survey data were not available for Burkina Faso or comparable low-income settings, we followed the World Bank approach of using the Value of Statistical Life Year (VSLY) based upon survey data from the Organization for Economic Co-operation and Development (OECD) countries.[21] These estimates were adjusted for the annual Gross Domestic Product (GDP) per capita of Burkina Faso[22] and income elasticity of VSLY of 1·2 (or 1·0 to 1·4 as low and high estimates for sensitivity analyses), as recommended by the World Bank, to reflect the difference in individuals' WTP for mortality risk reductions in low *vs* high income countries.[21] The future costs of mortality impact incurred beyond the year of exposure were discounted at the annual rate of 6%[21] for the main results, and 3% and 0% for sensitivity analyses.[23]

Annual crop deficits (from years with yields below 90% FCPI) were quantified in terms of kilograms of millet equivalent, and costed using the annual (September) Ouagadougou market price per kg in PPP-corrected 2011 USD as recorded by the National Statistics Institute of Burkina Faso.[24] As price data were available only over the period of 1997–2008, we used the average September price of this period for years outside this period and applied the Franc de la Communauté Financière d'Afrique (FCFA):USD exchange rate (1 January 2011[25]) of 490:1 CFA to USD.[26]

Additional analyses were performed based upon the upper and lower bounds of the model parameters as a way to explore the influence of parameter uncertainty on the results (see Supplementary Table 9–28 and Figures 9–1 to 9–4 in Annex 4).

The study was conducted following the ethical standards of the Declaration of Helsinki 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.

Role of the funding source

The funder of the study had no role in study design, data collection, data analysis, data interpretation, or the writing of the report. The corresponding author had full access to all the data in the study and had final responsibility for the decision to submit for publication.

Results

For the 29 years of observed crop data, annual crop yields were <90% of the period average in eight years, of which yields were <80% in two years (Figure 6–2, Table 6–1). The yield deficit in years with <90% of the period average yield is equivalent to an annual average harvest deficit of 18 kg/ae/year or 178 kcal/ae/day (averaged across all 29 years of crop yield observation).

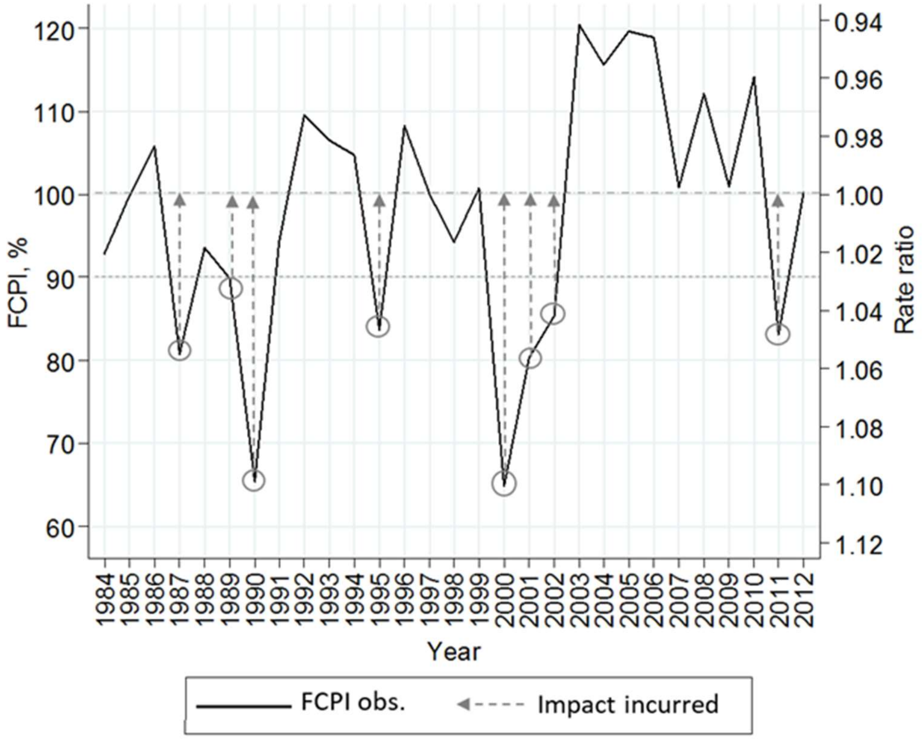

Figure 6—2. Time series of the Food Crop Productivity Index (FCPI) with the corresponding mortality risk ratio.

Circled markers indicate years with FCPI<90%. Arrows with dotted lines show the extent of the yield deficit below the counterfactual of 100% FCPI.

The mortality impact attributed to this annual average crop yield deficit was estimated as 7 child deaths <5 years of age or 438 YLL per 100 thousand people of all ages (Table 6–1, Figure 6–3). The attributed mortality impact reached 41 child deaths <5 years or 2,634 YLL per 100 thousand in the year 2000 when crop yield was the lowest in the observed period (Table 6–1). Over the period of 1984–2012, weather factors were estimated to account for 72% of the total mortality impact due to low crop yields (Table 6–1, Figure 6–3).

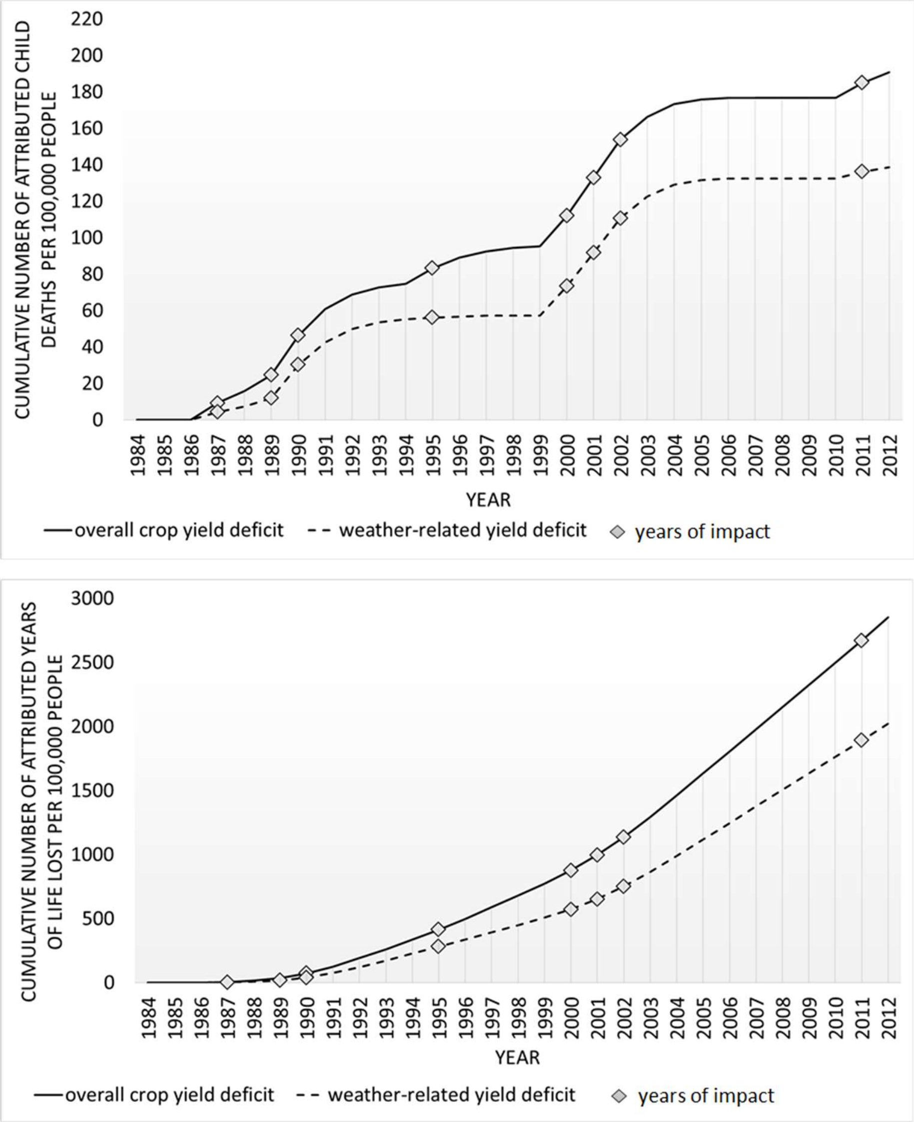

Figure 6—3. Cumulative health impact incurred over the period of 1984–2012 and attributed to the exposure in the year of birth to the overall and weather-attributed yield deficit in years with FCPI<90%.

Health impact is expressed in terms of the cumulative number of (A) deaths of children <5 years of age and (B) years of life lost (YLL) per 100 thousand people of all ages over the period of 1984–2012.

Table 6—1. Crop deficits and weather-related crop deficits, their attributed mortality impact and costs under the climate over the period of 1984–2012.

	Average year*		Worst year (2000)	
	Overall	**Weather-related**	**Overall**	**Weather-related**
Deficit in food crop harvest and yield				
kg per adult equivalent/year	18	14	110	106
kcal per adult equivalent/day	178	132	1,073	1,038
% FCPI below the period average	6%	4%	35%	34%
Mortality impact per 100 thousand people of all ages				
Child <5y deaths	7	5	41	39
YLL (not discounted)	438	331	2,634	2,529
Costs (thousand 2011 USD, PPP-corrected) per 100 thousand people				
Cost of grain to cover deficit	186	135	802	776
Monetized equivalent cost of YLL*, discounted at				
6%	260	196	1,552	1,490
3%	474	358	2,834	2,720
0%	1,166	882	6,974	6,695

*Based on deficits in years with FCPI<90% averaged across all years of the period 1984–2012.

**Using the period average VSLY of 2,663 USD for the average year and 2,647 for the worst year, i.e., 2000 (2011 USD, PPP-corrected).[21]

Table 6—2. Weather, crop yield, and attributable mortality impact estimates under 1·5 °C global warming for three 30-year periods centred on 2015, 2050, and 2100.

	IPSL-CM5A-LR			MIROC5		
	2015 (2000–2030)	2050 (2035–2065)	2100 (2085–2115)	2015 (2000–2030)	2050 (2035–2065)	2100 (2085–2115)
Selected weather parameters over crop growth season: 15 Mar–31 Oct						
Killing degree-days, °C	94	111	105	151	155	153
Precipitation, mm	848	862	793	817	829	852
Vapour pressure deficit, mm	6,098	5,992	6,141	6,275	6,234	6,286
Days without precipitation	69	69	72	66	64	68
Heavy precipitation events (>40mm/day)	0·03	0·06	0·10	0·03	0·03	0·00
No (%) years with yield deficit with FCPI						
<100%	22 (73%)	22 (73%)	21 (70%)	20 (67%)	22 (73%)	21 (70%)
<90%	11 (37%)	7 (23%)	17 (57%)	5 (17%)	13 (43%)	11 (37%)
<80%	1 (3%)	3 (10%)	2 (7%)	0 (0%)	0 (0%)	1 (3%)
Average annual deficit in food crop harvest						
kg per adult equivalent/year	18	14	28	8	19	16
kcal per adult equivalent/day	179	133	274	75	182	154
Child <5y deaths per 100 thousand people of all ages						
Average year*	7	5	10	3	7	6
Worst year (2000)	30	27	29	22	22	28
YLL per 100 thousand people of all ages						
Average year*	438	330	667	183	440	374
Worst year (2000)	1,938	1,748	1,852	1,380	1,401	1,773

*Based on deficits in years with FCPI<90% averaged across all years in the respective 30-year time periods.

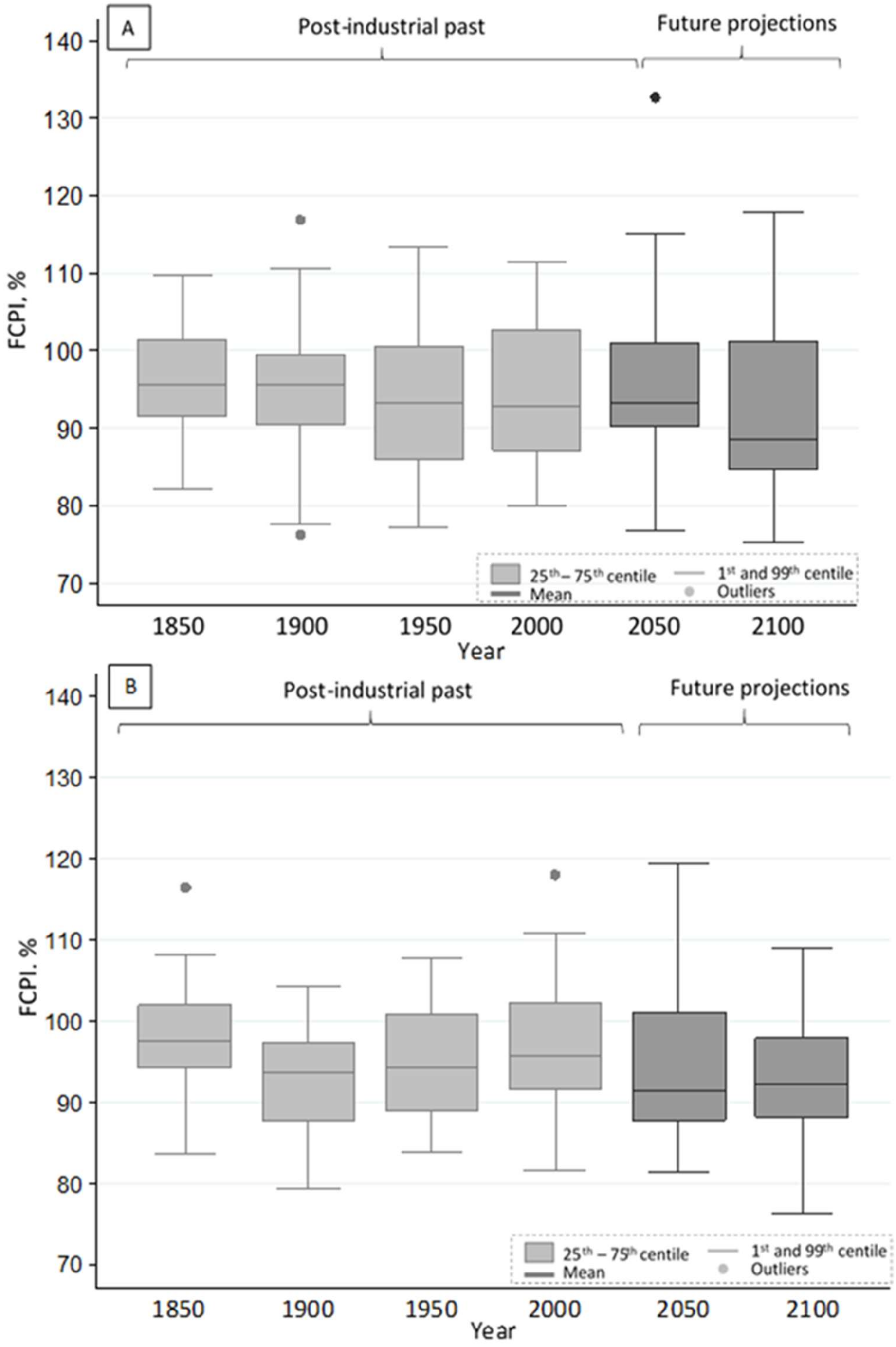

Figure 6—4. Food Crop Productivity Index (FCPI) projections based on climate data of each of the general circulation models separately: A – IPSL-CM5A-LR, B – MIROC5. Each box plot is based on data from a 30-year time period centred on the indicated year.

Weather projections under the 1·5 °C global warming target by 2100 suggest progressively less favourable growing conditions by the middle and end of the 21st century (Figure 6–4), mainly because of an increase in temperatures above crop tolerance levels and a decrease in precipitation (Table 6–2). The percentage of years with an FCPI <90% (of the average for the period from 1992–2012) was estimated to double from the period of 2000–2030 to the period of 2085–2115, correspondingly the mortality burden attributable to crop yield deficits would also double (Table 6–2, Figure 6–4).

The estimated annual average monetised cost of YLL per 100 thousand people from crop deficits in years <90% in the period of 1984–2012 was 260 thousand USD (2011 PPP-corrected rate) when a discount rate of 6% was used for future impacts (474 thousand and over 1 million USD per person per year using 3% and 0% discount rates) (Table 6–1). For comparison, the annual average cost of millet to cover the harvest deficit of these years over the same period was estimated as 186 thousand USD per 100 thousand people.

Additional analyses suggest a considerable range of uncertainty, if parameter uncertainty instead of their central estimates was considered in all of the above estimates (see Supplementary Tables 9–28 and Figures 9–1 to 9–4 in Annex 4).

Discussion

The evidence we present here provides, to our knowledge, the first empirically grounded quantitative estimates of the impact of low crop yields and their weather-attributable component on child mortality in a subsistence farming population of sub-Saharan Africa. In the Nouna HDSS population, on average each year, 7 child deaths <5 years of age or 438 YLL per 100 thousand people of all ages were attributed to low crop yield. The impact reached 41 deaths or 2,634 YLL per 100 thousand people in the year with the worst yield over 1984–2012. The monetised equivalent of this impact exceeded the cost of millet required to cover the corresponding harvest deficit. With the weather patterns projected under 1·5 °C global warming trajectory, our estimated mortality impact could double by the end of this century. Although based on models and data specific to the Nouna HDSS population of Kossi province, Burkina Faso, our findings are likely to be broadly indicative of the impact of low crop yields in other similar populations in the region.

The impact estimates reflect the evidence of an adverse effect of low crop yield in the year of birth on child survival to the age of five years. Over the period of observation, the additional mortality from crop yields <90% of the period average represented around 3% (95% CI 0.4–19%) of all-cause mortality in children <5 years in that period. Our model of health impact was based only on the mortality impacts of low yields in the year of birth and its results may not capture the full health burden of the cumulative lifetime exposure to low crop yields. Other epidemiological evidence suggests that *in utero* exposure and low crop yields in later childhood, adolescence, and adulthood may also have negative effects on health and survival.[4] Furthermore, our estimates did not consider morbidity impacts related to undernutrition and the associated increased susceptibility to infectious diseases, nor did we consider compromised cognitive development and immunity, or compromised productivity later in life.[4] Currently, the epidemiological evidence is too insecure to allow the development of a health impact model that integrates all of these effects, but they may add appreciably to our current estimates. Moreover, our results may represent a lower bound estimate of impact attributed to crop yield deficits, as we defined the deficits in relation to the period average crop yield level, which may be sub-optimal for the nutritional needs of this population.[27]

Our models provide a broad estimate of the potential value of the health costs of low crop yields in a subsistence farming population, hence, of the expenditure that might be justified to protect against that health cost. The annual estimate is around 260 thousand USD per 100 thousand people. The monetised cost of our estimated impact appears to be appreciably greater than that of the amount of millet that was needed (186 thousand USD per 100 thousand people) to compensate for the harvest deficit of low crop yield years (although the cereal crop costs we show do not include the costs of managing a programme of food distribution). Even without accounting for the full health burden of the cumulative lifetime exposure to low crop yields and possible loss of productive potential, it is important to examine possible strategies that could reduce the effects of such low yield years.

It was beyond the scope of this paper to consider what form such strategies or interventions might take. Determining this is a complex scientific undertaking and requires the assessment of a range of factors and implementation research. However, as our weather-crop yield model shows, low crop yields are largely attributable to the vagaries of the weather, which, in turn, are exacerbated by climate change.[29]

Moreover, applying the model to daily weather data generated under the 1·5 °C global warming target suggests that crop yields will fall over time (all other things being equal) as growing season temperatures rise and the distribution of precipitation becomes less reliable. This observation adds to the case for greater climate change mitigation aiming to limit global warming to 1·5 °C by 2100 but also provides added rationale for intervention, suggesting that efforts targeted specifically at ameliorating the effects of weather on crop yield should be considered (e.g., use of drought resistant seeds or improved irrigation). Nutritional protection measures and interventions such as food and supplement distribution, conditional cash transfers, food-for-work programmes, crop insurance schemes or other support might also be appropriate.[28] We must note here that we examined only one of the future climates which assumes 1·5 °C of global warming by the end of the 21st century – a target the achievement of which remains uncertain. The impacts are likely to be greater under other climate change scenarios projecting a greater extent of global temperature increase (2 °C and more)[29] and requires further investigation. Nevertheless, our results support the urgent need to limit any further global warming to 1·5 °C above pre-industrial levels.

With any modelling study, there are uncertainties and limitations. As described above, the method used to derive estimates of impact was limited to the mortality effect of the exposure to crop deficit only in the year of birth, and did not include the full range of outcomes and cumulative exposure that may also be important. Several of our modelling inputs, including the central exposure–response (yield–mortality) function, which was derived from a single relevant study available to date,[4] and modelled crop yield based on assumptions detailed in the Annex 4, were based on limited data and therefore have uncertainty that is only partly reflected in the confidence intervals. There is also technical uncertainty (and some ethical debate) over the calculation of the statistical value of a life year and social discount rate applicable in low-income settings.[30,31] The estimates of potential mortality burden with weather parameters projected under climate change were based on just two general circulation models relating to one (fairly uncertain) future climate scenario, and without any attempt to account for the (uncertain) trends in non-climate factors (e.g., socio-economic development). The model results should therefore be regarded as approximate rather than precise estimates, but they nonetheless offer valuable insights into the magnitude of the health burdens and the scale of interventions needed to prevent them. It is noteworthy that the full health and wellbeing burden of the cumulative lifetime exposure to low crop yields is likely to be far greater than our estimated impact.

Future research on health impacts of crop yield variation in the context of weather variability should attempt to address a broader set of health outcomes and wider aspects of their temporal effects beyond the effect of the exposure in the year of birth. To strengthen the evidence and provide more conclusive policy advice, similar modelling studies are required in other settings with a high prevalence of rain-fed subsistence agriculture. Such studies require further epidemiological evidence for the exposure–response function of crop yield variation and health outcomes from other settings, as well as meta-analytical estimates of this function across settings once more empirical studies are available.

This study contributes evidence for an appreciable impact of low crop yields on population health in the subsistence farming population of the Nouna HDSS. Much of this health impact appears to be related to the negative agricultural impact of increasing weather variability, which is likely to worsen due to climate change (all other factors being equal). The higher cost of the estimated mortality impact as compared to the cost of millet required to compensate the harvest deficit suggests that there is value in considering the development and implementation of strategies to protect against the effects of low crop yields and the adverse impact of weather on crop yield.

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6.2. Commentary on Paper 4 *The mortality burden of low crop yields in the context of current and future climates*

The analyses of this chapter suggest that there could be appreciable child mortality impacts in the Nouna HDSS population attributable to annual crop yield deficits, and that those impacts could become greater over time due to climate change (if all other circumstances remain unchanged). In the recent past (which here was used to approximate current conditions) the average annual impact of the exposure to low crop yield in the year of birth alone was estimated as 7 child deaths or 438 YLL per 100 thousand people of all ages. The monetary cost of this impact (in terms of the monetized equivalent of the years of life lost) appears to exceed the estimated cost of millet required to cover the associated crop yield deficit. Around two thirds of the estimated impact could be attributed to adverse weather effects on crop yield deficit. Under the future weather conditions, other conditions assumed constant, these impacts are projected to increase even under the most conservative climate change trajectory of 1.5 °C global warming by the end of the 21st century.

A number of methodological questions merit discussion in relation to the interpretation of the findings of this chapter.

(i) The use of a single empirical study to define the yield–mortality relationship

The risk ratio of child mortality in relation to annual crop yield deficit used in the impact model was based on the results of the single study reported in Chapter 5. To my knowledge, this is currently the only study that has evidence of this relationship for the target population. While specific, and hence directly relevant to this population, the availability of only one such study adds to the uncertainties of the model estimates, which would be more secure if it was based on a meta-estimate of risk ratios from a number of studies in similar populations. Therefore, in this chapter the estimated magnitude of the attributable child mortality burden is premised on the assumption that the association yielding the risk ratio of child mortality in relation to annual crop yield (identified in Chapter 5) is causal and provides an unbiased estimate of the risk ratio.

(ii) The counterfactual and limited interpretation of effects in worst affected years

The analysis was based on an assumed counterfactual to the extent that negative mortality impact is incurred only with yield reductions below the period of average yield level (i.e., <100% FCPI). Additionally, I applied a conservative assumption that this impact was incurred only in years when yields were below 90% of the period average (i.e., <90% FCPI). These are somewhat arbitrary figures that had to be assumed because the yield–mortality relationship (established in Chapter 5 and here used to model the attributed mortality burden) was based on a linear association which could not determine a level of crop yield that is no longer associated with additional risk for child survival. Therefore, estimates in this chapter are hypothetical as relates to what the impact could be if crop yield had a negative impact on child mortality under the assumed counterfactual level. Additionally, the limited capacity of the yield–mortality relationship (established in Chapter 5) to account for any differences in the magnitude of the effect of more extreme *vs* moderate reductions in crop yield somewhat limits conclusions about the estimates of the child mortality burden in more severely affected years.

(iii) Indirectness of the monetary estimates and their underlying assumptions

The monetary estimates of the value of child mortality impact of low annual crop yields in these analyses were indirect and heavily dependent on assumptions. I followed the welfare-based approach of estimating the value of child mortality impact. Given the lack of data on people’s willingness to pay for a reduction in the risk of mortality in low income countries, I followed the World Bank approach of using the VSLY derived from data on people’s willingness to pay from high-income countries, indirectly adjusting for the macro-economic parameters of Burkina Faso, namely GDP and income elasticity [146]. This approach has been subject to methodological and ethical debates, e.g., over the difference in the value of life in high *vs* low income countries, reflected by the assumed value of the income elasticity parameter. Further debate exists around the value of the discount rate applicable in valuation of future health costs. While the World Bank suggests using 6% discount rate for low-income countries [146], a discount rate of 3% has been widely used in high-income settings as well as for globally comparable estimates, such as produced by the Global Burden of Disease project [147]. When considering the cost-effectiveness of an intervention, discount rates conventionally are applied to both costs and benefits simultaneously [148]. Although I did not attempt formal cost-effectiveness analyses, to contextualise the cost of this burden, I presented the cost of millet that would be required to cover the crop yield deficit that the burden was attributed to. Future costs only concerned mortality impact and not the expenses on millet, as the latter were assumed to be fully incurred in the year of exposure to low yield, while the former incurred in the year of exposure as well as four following years (till the exposed children reached 5 years of age since their exposure in the year of birth). As no future costs of millet were applicable, and hence, no discount rate could be applied to the cost of millet, it might be argued that there should equally be no discount rate applied to the cost of the attributed mortality burden. Depending on the choice of the value of income elasticity and the discount rate alone, the monetary value of the burden of child mortality attributed to low crop yields could range from the lower estimate of 127 thousand USD (assuming income elasticity of 1.4 and discount rate of 6%) to the upper estimate of over 2 million USD (assuming income elasticity of 1.0 and discount rate of 0%). The range between the lower and upper estimate is even greater when other sources of uncertainty, e.g., statistical uncertainty around the exposure–response function, are taken into account (see Table 9–28 in Annex 4).

(iv) Attribution of crop variations to weather

Estimates of the extent to which the attributed mortality burden could be related to adverse weather effects on crop yields depended upon the extent to which the statistical crop yield models captured these effects. Data for the model calibration was imperfect with regards to the geographical resolution of crop yield, soil conditions, the start and duration of the cultivation season, timing of crop plant growth stages, and agricultural management. Nevertheless, the model explained large parts of crop yield variation (51–95% across different crop types) over the period of 1984–2012 (see Annex 4). However, it remains unclear whether and how much of the crop yield variation that was not explained by the models could be attributed to weather variation, e.g., if more comprehensive and better quality data were available. Therefore, the reported proportion of the weather-related impact is constrained to the ability of our models to explain yield variation by our examined weather variables, which might not have been exhaustive. The assumptions taken for each of these models are detailed in Annex 4.

(v) Extrapolation

Some extrapolation was used to estimate the mortality burden attributable to crop yield in the recent past, as the yield–mortality risk ratio was derived for the period of 1992–2012 (Chapter 5) but applied to crop yield data over a longer period of 1984–2012 in this chapter. Hence, these calculations assumed that the yield–mortality risk ratio in the period 1984–1991 was equal to the yield–mortality risk ratio in the period of 1992–2012.

Larger assumptions related to extrapolation were applied when modelling the attributable burden of mortality under the future climate change trajectory. Firstly, I assumed that the yield–mortality risk ratio, which was derived using data over the period of 1992–2012, remained the same in the future up to the year 2100. Secondly, I assumed that parameters of the crop models calibrated using agricultural production and weather data from the period of 1984–2012 would be equally applicable in the future up to the year 2100. The range of projected weather variability under the 1.5 °C global warming trajectory remains largely the same as it was observed in the recent past. However, it is unclear how other changes, e.g., economic development and any changes in agricultural production practices may influence associations defined by these models. Therefore, estimates provided under climate change should not be viewed as a prediction of future impacts but more as a ‘thought experiment’ of what the impact could be if the Nouna HDSS population now (under the current socio-economic and other conditions) was experiencing the weather patterns, which are projected by the end of this century under the 1.5 °C global warming trajectory.

(vi) Uncertainty around weather patterns

It is uncertain whether the target of limiting global warming to 1.5 °C be attained by the end of the 21st century [149]. Therefore, the estimates derived under the future weather variability model represent a very conservative assumption of climate change. The two series of weather conditions projected by the GCMs represent weather conditions that would result from changes in the physical processes in the atmosphere, ocean, cryosphere, and land surface in response to the increasing greenhouse gas concentrations in the atmosphere [6]. The advantage of using GCM weather projections over simpler models (e.g., stochastic weather generators) is the physical plausibility of these models, which ensures the consistency of the model results geographically across regions as well as across different weather variables (which are often correlated with each other, e.g., colder temperature and less solar radiation on rainy days than on dry days and other more complex relationships) [150]. To account for uncertainty across different GCMs, the IPCC 5th assessment presented weather projections using an ensemble of around 40 GCMs [151]. Weather projections for the 1.5 °C trajectory were generated only recently and work on the GCMs for 1.5 °C trajectory was still in process, with only three GCM weather projections available from the ISI-MIP team when I started analyses for this study. One of these GCMs was unable to correctly reproduce past weather conditions for my study setting, and therefore, was omitted from my analyses. The use of only two GCMs limited the extent to which I could account for the uncertainty of weather projections.

To further characterise the uncertainty of the theoretical risk of crop yield deficit in any specific year, I considered using a weather generator, such as the LARS WG [152]. LARS WG is a numerical model that produces synthetic daily time series of weather variables (e.g., precipitation, temperature, solar radiation), which are unlimited in their possible length, thus, permitting one to estimate the *chance* of observing a specific weather pattern. These series are based on statistical patterns derived from observed weather data in the past (for future weather projections GCM-based climate change assumptions can be applied). However, I eventually discarded this idea as weather generators do not properly account for the correlations between different weather parameters, notably rainfall and temperature, and hence, might bias crop model-based yield estimates. Instead, I used GCM-weather projections for the 30-year period centred around each year of interest to illustrate the uncertainty of the theoretical risk of crop yield deficit (see Figure 6–4 and Table 6–2).

6.3. Consistency with other evidence

As a part of developing estimates of the burden of child mortality attributable to low crop yield in the context of weather variability, this chapter contributed some empirical evidence of the link of crop yield variation with weather variation in Kossi province. It suggested that, depending on crop type, 50–86% of variation in their annual yield over recent years can be statistically explained by variation in such weather factors as crop growing season cumulative rainfall, growing degree days, killing degree days, dry spells and days without precipitation, heavy rainfall events, solar radiation, and mean vapour pressure deficit. These estimates are broadly consistent with other estimates of the link between crop yield variation and weather in sub-Saharan Africa [32,59].

I am not aware of other estimates of the burden of child mortality attributable to crop yield reductions comparable to the results in this chapter. The focus of this chapter on estimating a burden of child mortality that could be attributed to weather-related crop yield reductions is consistent with prior findings relating to the association of child mortality with factors that are related to both, crop yield and weather patterns, such as weather shocks during the crop growing season and NDVI variations [94,95,100,107,108,111,112].

Lloyd *et al* provided other estimates of climate change impact using global modelling methods of distributional shifts in food energy availability and child stunting arising from climate change impacts on agricultural production, prices, and trade [49,71]. Hence, my estimates of climate change impact on child mortality (based on individual-level empirical data) are not directly comparable to Lloyd *et al's.* However, the estimates of additional child mortality related to changes in crop yields under 1.5 °C global warming were reasonably similar: 3 child deaths per 100 thousand people of all ages in my estimates *vs* 4 deaths per 100 thousand people of all ages in Lloyd *et al's* estimates. (I derived the latter rate using the projected population of 679 million people in Western sub-Saharan Africa [153] by the year 2050 and Lloyd *et al's* result of additional 26,700 child deaths from stunting under the age of 5 years in Western sub-Saharan Africa that they attributed to a global mean temperature increase of 1.5 °C by 2050 assuming a low growth pathway [71].)

6.4. Implications of Paper 4 *The mortality burden of low crop yields in the context of current and future climates*

This chapter provided insight into the burden of child mortality that could be attributed to annual crop yield deficits experienced currently (approximated by the recent past) and under the weather conditions of the most conservative climate change scenario of global warming by 1.5 °C by the end of this century. These estimates were based on the empirical results of the association of child mortality with low crop yield in the year of birth, provided in Chapter 5, which here was assumed to be causal. The findings in this chapter demonstrate the importance of crop yield as an epidemiological risk factor for child health in the Nouna HDSS population, suggesting that there is value in considering possible response strategies.

The expenditure that might be justified to minimise the risk of child mortality associated with low crop yields in this setting, based on the adjusted estimates of the willingness to pay for the risk reduction, was estimated as 260 thousand USD (2011 PPP-corrected rate) (when a 6% discount rate is assumed). Although this estimate did not take into account the full health burden of the cumulative lifetime exposure to low crop yields and possible loss of productive potential, it appears to be greater than the cost of millet that was needed to compensate for the harvest deficit (186 thousand USD per 100 thousand people), at least under the assumptions used to derive the central estimates of the cost of the mortality burden. This may suggest value in further investigation into the possible response strategies and their cost-effectiveness.

Most of the crop yield variation in Kossi province appeared to be related to weather effects on crop yields. Weather conditions are likely to become less favourable for crop production in this area even under the most conservative climate change trajectory of a 1.5 °C increase in the global mean temperature by the year 2100. Correspondingly, the results of this chapter suggested a possible increase in the attributed burden of child mortality with the future weather conditions. However, these estimates took no account of possible future changes in the social, economic, and other factors that are likely to be changing along with the climate. Such changes may modify the estimated impacts of the crop yield deficit on child mortality. Therefore, the estimates of the future attributable burden presented in this chapter should not be viewed as a prediction of what the impact is expected to be but only as a ‘thought experiment’ showing what the impacts could be under my set of my assumptions (as detailed earlier in this chapter), which includes the assumption of no changes in any other future conditions except weather.

A comprehensive estimate of the full possible burden of child mortality, undernutrition and its associated morbidity as well as the long-term health and productivity consequences was beyond the scope of this chapter and this thesis. Such estimates require further development of empirical associations of these outcomes with annual crop yield variation to enable the full range and magnitude of the attributed impact to be accounted for. Similar estimates are also required for other contextually similar subsistence farming populations. Further investigation should be undertaken on the possible response strategies, their effectiveness in preventing negative health impacts, as well as their cost-effectiveness. Finally, further modelling studies could be undertaken to estimate the possible magnitude of the attributed health burden under climate change scenarios other than the 1.5 °C trajectory, which may not be the most realistic scenario, given the current levels of greenhouse gas emissions [149].

Nevertheless, this chapter provided an insight into the possible (although likely lower-bound estimate) of the magnitude of child mortality impact of low annual crop yield in the Nouna HDSS population in the context of current and future weather variability. If the associations used to estimate these impacts are causal, the results of this chapter suggest that annual crop yield is a notable epidemiological risk factor in this area requiring appropriate response strategies.

In the next chapter I will discuss the findings of this thesis in relation to the thesis aim and objectives, highlight its contribution to the body of knowledge, acknowledge the overall thesis limitations, and suggest areas for further research as well as possible policy implications.

Chapter 7: Discussion

In this chapter I discuss my thesis findings and lessons learned from my research. It has the following sections:

7.1: reflection on the thesis focus,
7.2: key findings of the thesis,
7.3: original contribution to the body of knowledge,
7.4: general thesis limitations,
7.5: suggested areas for future research,
7.6: policy implications,
7.7: conclusion.

7.1. Reflection on the thesis focus

My original interest was the potential effects of drought and drought-related health outcomes in subsistence farming populations in low-income settings and how they might change with climate change. Of particular interest to me were the under-studied indirect effects of climate change, operating through less extreme reductions in food availability and crop harvest from adverse weather conditions during the growing season. It is not possible to study such impacts directly as this would require observation over very long time periods (measured in decades) of changing climate, and the degree of climate change in the recent past remains small by comparison with the expected changes in the coming decades. I therefore chose to study specific elements of the possible pathway by which climate change, or more specifically, changes in weather patterns, lead to such impacts, as reflected by the links “weather variability – crop production”, “crop production – child undernutrition”, “crop production – child mortality”, “child undernutrition – child mortality” (see sections 1.1 and 3.1). These connections can all be studied directly based on current (recent past) data on variations between individuals and years.

I selected the Nouna HDSS area in rural Burkina Faso as a location where this impact pathway is likely to be one of the key processes through which climate change may impact child undernutrition and health. The vulnerability in this area was suggested by high levels of subsistence farming relying on rain-fed agriculture, which is potentially sensitive to unfavourable weather patterns. Furthermore, the presence of the HDSS site and national agricultural data provided a unique opportunity for longitudinal analyses pertaining to my research question (see the section 3.2).

I chose to focus on children <5 years, as they are likely to be particularly vulnerable to undernutrition [154] and hence to the potential effects of weather on crop availability, and in the future, to climate change. Furthermore, childhood undernutrition is particularly important from a public health perspective, as its legacy effects continue into adulthood, including increased susceptibility to infectious [155] and chronic disease [154], the risk of compromised cognitive development [156], and lower economic productivity [157].

Note that, because I was interested in the pathways operating through food availability and nutrition, I did not attempt time-series analyses of the link between weather variability and the health outcomes, which could represent the effect of a range of pathways including the immediate and direct effects of temperature. Most such analyses are undertaken using time series analysis methods and focus on the short-term associations with lag times between the exposure and outcome measured in days [158]. Such study design is mainly intended for the study of the direct impacts of weather variability on health, e.g., the short-term effects of heat or cold, suggesting their short-term associations with excess mortality, mainly related to cardiovascular, respiratory, and other chronic diseases [159,160]. One such study has been published on the population in the Nouna HDSS, suggesting a direct effect of heat on daily child mortality with a delay in 0–1 days, and an effect of high rainfall on daily mortality among the elderly with a delay in 2–6 days [161]. Other study designs, e.g., difference in difference analyses, have been used to study the long-term effects of weather variability, mainly rainfall and temperature shocks, on child undernutrition and mortality [78,107,112]. Such analyses have been previously completed in Burkina Faso, associating monthly and yearly rainfall deviations from their long term averages with child mortality [107] and the anthropometric height-for-age index, used to determine stunting [78]. Some of these analyses examined rainfall deviations specifically during the crop growth season, attempting to approximate their possible impact on crop yield [78]. However, their design is still susceptible to alternative explanations other than the impact pathway through crop yield variation, e.g., through weather-sensitive infectious diseases and income [78]. My more reductionist approach, focusing on individual links in the hypothesized causal chain, enabled the analysis of specific inter-relationships relevant to the weather–crop yield–nutrition–survival pathway.

7.2. Key thesis findings

The findings of this thesis addressed several substantive questions, helping to characterise potential risk for child undernutrition and mortality related to low crop yields, such as might arise from adverse weather conditions during the crop growing season, under the current and future climate. The questions were addressed by examining individual links in the hypothesized causal chain in a sub-Saharan subsistence farming population of the Nouna HDSS in rural Burkina Faso in response to the thesis objectives. This section summarizes how these findings helped to address the gap in the evidence of crop yield variation as an epidemiological risk factor for child undernutrition and mortality in the context of weather variability.

(i) Does low household crop harvest pose a risk for child undernutrition?

In response to the first objective, Chapter 4 studied the link between food energy availability from household crop harvests and children's nutritional status, as measured by MUAC. If results of this chapter are interpreted as causal, they suggest that low household cereal crop harvests (<3,000 kcal/ae/d in their food energy value) pose a risk for child undernutrition in the Nouna HDSS area even in a year of average agricultural productivity.

Analyses of similar associations of household crop production measures with children's nutritional status in other settings did not always suggest such risk. For example, studies in Northern Laos and Papua New Guinea found no evidence for the associations of child anthropometric measures with rice harvest and the amount of crop cultivated [86,88]. Overall, published evidence on this question is currently inconclusive.

However, in the Nouna HDSS, it was highly plausible for children's nutritional status to be sensitive to the harvest of cereal crops. As discussed in Chapter 4, cereal crops are key source of food energy in Burking Faso [122] and almost all of our analysed households cultivated cereal crops for their subsistence needs. Among the examined households that produced low crop harvests (<3,000 kcal/ae/d), there was an appreciable proportion (15%) of acutely undernourished children. Hence, it is likely that in the Nouna HDSS low household crop harvest could be a risk factor for child undernutrition.

In the year of average crop productivity conditions, food energy produced from cereal crop harvest in about half of the examined households exceeded 3,000 kcal/ae/d level only marginally (Chapter 4). In worse crop productivity conditions, a greater proportion of households might experience harvest levels that provide less than 3,000 kcal/ae/d, thus, possibly exposing a greater number of children to inadequate food availability and the associated risk of undernutrition. Only a small number of the households produced much larger harvest levels (up to 16,052 kcal/ae/day), which might remain resilient to crop yield variations.

(ii) How big a risk does low annual crop yield pose to child undernutrition?

As opposed to the previous question on the effect of lower crop harvest in one household compared to another, this question concerned changes in food availability across years. It was addressed by responding to the second thesis objective in Chapter 5, which studied the relationship of child nutritional status (measured by MUAC) with annual crop yield variation in Kossi province. If the identified associations are interpreted as causal, they suggest that on average in the Nouna HDSS child MUAC was lower in years with lower provincial crop yield. They also suggested lower average MUAC among children that experienced lower crop yield throughout their lifetime, as averaged across the years of their life up to the year of MUAC measurement. However, results of these analyses did not provide evidence for lower child MUAC to be associated with lower crop yield in the year of birth, which could be explained by the nature of the measure of MUAC to reflect short-term changes in food intake [136].

Results of similar studies (but using different exposure and outcome measures) in other settings were consistent with these findings. A longitudinal panel data analysis suggested some evidence of the association of per capita crop availability with severe wasting (measured using the weight-for-height index) in selected areas of Ethiopia [101]. Studies of the effect of spatial variation of crop growing conditions, approximated by NDVI and EVI, provided evidence for a lower risk of child wasting associated with higher NDVI over the crop growing season in the year of child measurement in Nepal [96] and Mali [94]. Yet, further studies are necessary to contribute a weight of evidence for annual crop yield variation as a causal risk factor for child undernutrition. If interpreted as reflecting causal associations, this evidence suggests that lower annual crop yield in Kossi province may increase the average risk of child acute undernutrition in the Nouna HDSS and possibly in similar subsistence farming populations.

(iii) How big a risk does low annual crop yield pose to child survival?

Chapter 5 also studied the relationships of child survival with annual crop yield variation. It provided evidence for a lower probability of survival in children of the Nouna HDSS area that were born in years of low food crop yield in Kossi province. This evidence was based on comparisons of *year-to-year* changes in provincial crop yield in relation to the differences in the survival of children born in one agricultural year *vs* another till they reached 5 years of age. Furthermore, Chapter 5 also provided evidence for the separate association of annual crop yield with child MUAC and the association of child MUAC with survival. These findings suggested that poorer nutritional status may in part explain the lower survival among children born in years of low yield.

The evidence for the association of child survival with annual crop yield in the year of birth is broadly supported by results of similar associations of child survival with annual variation in food crop production in Tanzania [99], with spatial differences in NDVI in Burkina Faso and in other West African countries [94,95], with seasonal differences in food availability in Gambia [139,140], and with rainfall shocks in Burkina Faso and Mali [78,107]. Yet, again further studies are necessary to strengthen the evidence for *year-to-year* variation in crop yield as a risk factor for child survival.

(iv) What burden of child mortality was attributable to low annual crop yield?

In response to the third thesis objective, Chapter 5 estimated the burden of child mortality that was attributable to the exposure to low crop yield in the year of birth to illustrate the importance of crop yield variation as an epidemiological risk factor for child health in this setting. The average attributed burden in the recent years was estimated to be 3% of all-cause mortality in children <5 years of age in the Nouna HDSS. Although this may appear to be a small proportion in relative terms, it translates into a sizable loss of human life in absolute terms – on average each year of the period 1984–2012 438 YLL per 100 thousand people of all ages were attributed to crop yield reductions below the period average yield level. In the year of the worst yield level (year 2000) the attributed impact reached 2,634 years of life lost per 100 thousand people of all ages.

By adjusting estimates of the willingness to pay for removing the risk of mortality in high income countries to the macroeconomic parameters of Burkina Faso, a justifiable expenditure for removing the risk of low crop yield for child mortality in this setting could be 260 thousand USD per 100 thousand people per year. This estimate did not account for the full health burden of the lifetime exposure to low crop yields and possible loss of productive potential. Nevertheless, it appeared to be greater than the cost of millet that was needed to compensate for the harvest deficit, suggesting value in further investigation into the possible response strategies.

(v) What proportion of this burden is attributable to weather effects on yield?

Based on the statistical crop model co-developed with my research collaborators, Chapter 6 suggested that, depending on crop type, 50–86% of variation in their annual yield over the recent years could have been statistically explained by variation in our examined weather parameters. According to my estimates, about 72% of the burden of child mortality that was attributed to the overall crop yield variation in Kossi province could be attributed specifically to the proportion of crop yield variation that was explained by the variability of weather conditions. Hence, weather variation appeared to be an important driver of crop yield variation, and correspondingly, its attributable child mortality burden in the Nouna HDSS area.

(vi) How could the attributed child mortality impact change with climate change?

Chapter 6 further explored how the attributed burden of child mortality could change under the weather variability projected with climate change. The estimates were made for the most conservative scenario of global warming by 1.5 °C by the end of the 21st century, corresponding to the target agreed under the UNFCCC in Paris in 2015 [162]. This scenario suggests that there will be progressively less favourable growing conditions for the crops in Kossi province by the end of the 21st century with an increase in temperatures above crop tolerance levels and a decrease in precipitation. A ‘thought experiment’ of what the impact would be if the Nouna HDSS population now (under the current socio-economic and other conditions) was experiencing the weather patterns, projected for the end of this century under the 1.5 °C global warming trajectory, suggested that the burden of child mortality attributed to crop yield reductions could be up to two times higher (an increase from 7 to 10 child deaths or from 3 to 6 child deaths per 100,000 people of all ages, depending on the climate model). Although these estimates are only theoretical and do not account for future changes in conditions other than weather, these are the first empirical estimates of such possible impact in a vulnerable subsistence farming population.

Summary on crop yield variation as an epidemiological risk factor

By addressing the above questions, this thesis contributed to the evidence of the core associations in the hypothesised pathway of weather variation diminishing crop yield, and therefore, contributing to child undernutrition and mortality in the subsistence farming population of the Nouna HDSS in rural Burkina Faso. The wider body of knowledge, although lacking directly comparable studies, largely supported these findings suggesting that crop yield variation could be an important risk factor for child undernutrition and mortality in similar subsistence farming populations. As shown in the Nouna HDSS area, exposure to low crop yield in the year of birth alone appears to have a sizeable impact on child mortality, which could be averted at a relatively low cost. In areas relying on rain-fed agriculture and where climate change is projected to have a negative influence on crop yield, these impacts may intensify, as shown in Nouna, possibly even under the most optimistic climate change scenario.

To which other populations might these results apply?

The basic relationships of household crop harvest with child MUAC and of annual crop yield with child survival and MUAC identified in this thesis may also apply to other similar subsistence farming populations with high levels of child undernutrition and mortality and low levels of crop productivity (though context may mean appreciable variations from setting to setting). Subsistence farming populations of this type are particularly common in sub-Saharan Africa and South East Asia [163]. The further link with weather variation could also apply to those subsistence farming populations who rely on rain-fed agriculture to a similar extent as the Nouna HDSS population. However, the magnitude of these associations in other settings could be affected by contextual factors other than those in Nouna HDSS. Given the lack of directly comparable studies in different settings, it remains uncertain how magnitude of estimates derived from the Nouna HDSS could compare to other settings where prior studies attempted to examine the associations between crop yield/harvest, child nutritional status, and mortality.

7.3. Original contribution to the knowledge

This thesis contributed findings addressing the gap in evidence relating to the potential risks of child undernutrition and mortality related to crop yield variation, such as might arise from adverse weather conditions during the crop growing season, in subsistence farming populations. Specifically, I made the following original contributions, which were published in two peer-reviewed journal papers with an additional manuscript under review and another prepared for submission (Table 3–1).

i. New evidence of the association between household crop harvest and child MUAC by conducting the first study of such an association in the Nouna HDSS population. The limited number of prior studies were inconclusive suggesting evidence for association between household crop harvest and measures of child nutritional status in some settings but not in others. My findings substantiated the likely sensitivity of children's nutritional status in the Nouna HDSS to differences in the availability of food energy from household crop harvest. For the first time, I characterised a non-linear shape of this association, suggesting a level of harvest below which child nutritional status appears to be subject to risk related to low harvest levels.

ii. Evidence of the association of child survival with MUAC. Although this association is generally well-researched [21,80], it previously has not been investigated in the Nouna HDSS population in children of <5 years, except for neonates [164].

iii. New evidence of the associations of annual crop yield variation with child survival and MUAC. It suggested that children's nutrition and health are vulnerable to annual variations in crop yields in the area of the Nouna HDSS in Burkina Faso. Prior to this thesis, to my knowledge, these associations have only been examined by one study in Tanzania [99] and one study in Ethiopia [101]. These findings suggest the importance of ensuring good crop yields for child health and contribute to the understanding of development priorities in subsistence farming populations.

iv. Estimates of how the burden of child mortality that is related to crop yield reductions might change with 1.5 °C global warming by the end of this century. Prior to my work, possible changes in child undernutrition and mortality under climate change have been modelled using country-level data on child undernutrition and food availability, and hence, had a limited capacity to provide information on the magnitude of the impacts in vulnerable subsistence farming populations [47,49]. My estimates added perspective on the possible magnitude of impact that could be experienced specifically by subsistence farmers. Furthermore, these are some of the first impact estimates produced for the trajectory of 1.5 °C global warming, consistent with the aspirational climate change mitigation target expressed in the Paris Agreement [162].

The quality of evidence in this thesis was enhanced through the use of crop production data (as opposed to less accurate proxies, such as vegetation indices, used in most prior studies) and longitudinal Nouna HDSS data. This thesis demonstrated how the high-quality HDSS data in combination with the local environmental data (here agricultural and weather data) can be used to address complex research questions such as the evidence of pathways through which some of the most damaging indirect health impacts of climate change may occur. Similar uses of the HDSS data could help to address the lack of evidence relating to planetary health issues in low-income countries where these aspects have been understudied in large part due to the relevant data limitations.

Additionally, I contributed a detailed assessment of methodological shortcomings in studies of the drought impacts on child undernutrition, and provided suggestions to strengthen the rigour of future studies and their value in contributing to the weight of evidence.

I was honoured to receive four international recognitions for work completed as a part of this thesis (Table 7–1).

Table 7—1. Awards received in recognition of work completed as a part of this thesis

Award	Year	Awarding body	Awarded for
International Graduate Scholar Award	2014	Common Ground Research Network: Climate Change Impacts & Responses	Overall subject expertise and experience
Outstanding student poster award	2016	International Society for Environmental Epidemiology	Poster presentation on Paper 2 (Chapter 4)
International Emerging Scholar Award	2017	Common Ground Research Networks: Climate Change Impacts & Responses	Overall subject expertise and experience
Finalist for Tyroler Prize Paper Award	2017	Society for Epidemiologic Research	Paper 3 (Chapter 5)

7.4. General thesis limitations

While this thesis contributed original evidence and impact estimates relating to crop yield variation as a risk factor for child undernutrition and mortality in a subsistence farming population in the context of weather variability, it has some limitations. Limitations specific to each analysis are discussed in the respective chapters. This section discusses the overall limitations of the thesis.

(i) Data constraints

As explained in Chapter 4, household crop harvest data were self-reported and hence potentially subject to some inaccuracy and bias. The high quality longitudinal Nouna HDSS data in conjunction with the provincial agricultural statistics available in Kossi province allowed the core associations of annual crop yield variation with child survival and MUAC to be identified. However, much larger sample (more years of data) was needed to assess any possible threshold effects in these associations. There was also limited opportunity for formal analysis of the mediation of the effect of low annual yield on mortality by MUAC to determine the extent to which this effect is related to deterioration in child nutritional status. Analyses in relation to mortality caused by undernutrition were not possible due to the low number of deaths recorded with this cause in the Nouna HDSS. Further data limitations included the non-random selection of children for MUAC measurements in the year 2010 (used for the analyses in Chapter 4), and the lack of anthropometric measurements other than MUAC, which could be used to explore their associations with crop harvest/yield and consistency of such associations with those identified here in relation to MUAC.

(ii) Relevance to extreme yield deficit

The findings of the associations of annual crop yield with child MUAC and survival presented in Chapter 5 and the related estimates of the attributable effect in Chapter 6 did not elucidate any possible differences in the effect of extreme *vs* moderate crop yield deficit across years and across households. Analyses presented in Chapter 5, were based on statistical models that assumed a linear shape of the examined associations, which did not permit me to differentiate the magnitude of effect in years with the worst *vs* least yield deficit. Furthermore, the period of data available for the analyses (1992–2012) did not include some of the greatest extremes in crop yield deficit known in this area, e.g., in the 1970s and early 1980s [165–167], thus limiting the relevance of the identified effect size to more extreme yield deficits than those observed over 1992–2012. Analyses in these chapters were also constrained by the province-level resolution of yield data, which does not contain information on any possible differences in yield deficit across individual households, and therefore, does not permit examining effect differences across households. Chapter 4 suggested an effect in relation to differences in harvest level across households in one year, but it is uncertain whether the magnitude of the nutritional effect of such harvest differences in one year are similar to the effect of differences in yield reduction level from one year to another. If longer a series of health and crop yield data at a more geospatially refined sub-province level were available, I would have examined any possible non-linearity in the associations of child survival and MUAC with annual yield variation, taking into account sub-province yield differences.

(iii) The possibility of residual confounding

Residual confounding is always a potential limitation. In my analyses of the association of child MUAC in relation to household crop harvest in Chapter 4, data was lacking on multiple possible sources of residual confounding, notably by socio-economic factors. I am not aware of major sources of residual confounding of the association of annual crop yield in relation to child mortality and MUAC in Chapter 5. Yet, I am conscious that the design of this analysis did not fully eliminate the risk of confounding by any unaccounted factors that vary from one year to another and are associated with variations in survival across birth cohorts and with annual yield, as elaborated in Chapter 5.

(iv) Uncertainty over the modelled impact estimates

In this thesis, estimates of the possible child mortality impact under climate change were provided only as a ‘thought experiment’ of what the impact might be if the future weather conditions were experienced now. These estimates were subject to high levels of parameter and structural uncertainty. The uncertainty from model parameters was reflected by sensitivity estimates derived from the combination of upper and lower 95% confidence interval bounds of the model parameters (yield–mortality risk ratio and crop model estimates). These suggested very wide bound of the model estimate uncertainty (see Supplementary Table 9–28 and Figure 9–1 in Annex 4). In future attempts to repeat such estimates, parameter uncertainty might be minimised through the further development of evidence on and meta-estimates of the yield–mortality association as well as the improved explanatory power of the crop models.

Additionally, structural uncertainty could be related to the selection of the most conservative climate change trajectory and the availability of only two GCMs for this trajectory. It is highly uncertain whether the target of limiting global warming to 1.5 °C by the end of this century will be achieved. Current greenhouse gas emission trajectories suggest that this could be the least likely climate change trajectory [149]. Furthermore, it is uncertain to what extent socio-economic and other contextual conditions could change in the Nouna HDSS area in the future, which therefore had to be assumed in my analyses to remain the same as they have been observed in the recent past.

7.5. Suggested areas for future research

The findings of this thesis provide an initial contribution to the area of study on crop yield variation as an epidemiological risk factor in subsistence farming populations in the context of current and future weather variation. Such early stage of research potentially creates an opportunity for a sizeable future research agenda. Further, I emphasise four possible directions for strengthening and expanding research on this risk factor and for the development of strategies to address its associated health risks.

(i) Strengthening the weight of evidence for the examined associations

Comparable studies to those presented in this thesis are currently lacking sufficient evidence to interpret the examined associations as causal. To strengthen the evidence base, similar analyses should be undertaken in other subsistence farming populations. To allow for appropriate syntheses and meta-analyses of their results, future studies should transparently report characteristics of their study populations and settings, contextual factors, study design, and methods.

The feasibility of repeating these analyses elsewhere depends upon the availability of suitable data. For example, analyses of crop yield variation in relation to child survival requires a long time series of agricultural production data and child survival data in sufficiently large populations. The necessary survival data could be derived from other INDEPTH HDSS sites in Africa and Asia. Yet, other HDSS sites may not have equivalent anthropometric data as in the Nouna HDSS, as these are not routinely collected across the INDEPTH Network. It is crucial to consider the quality of potential data sources. For example, I did not consider routine health care data on nutritional outcomes in Burkina Faso suitable for these studies, due to the limited health care access for a large part of the population [168].

(ii) Expanding the evidence to other outcomes

Besides replication, the evidence base should be expanded to other timings of exposure to yield variation, to a wider set of outcomes, to other age groups, and to possible non-linear characteristics of the examined associations. This thesis examined the child survival impact of exposure to annual crop yield variation only in the child's year of birth. Further research could attempt to examine cumulative lifetime impact of crop yield variation on the full range of nutritional and health outcome measures that could potentially be impacted. These include other aspects of nutritional status (e.g., chronic undernutrition and micronutrient deficiencies), cause-specific mortality and morbidities that individuals are more susceptible to in cases of compromised nutritional status (e.g., diarrhoeal and infectious diseases) [21]. Studies of events of extreme food deficit suggested their association with negative impact on an individual's development, productivity, income, and other descriptors of well-being in subsequent life [154–157]. Additionally, studies on extreme events suggested that negative health and nutrition impacts are associated also with exposures to extreme food deficit in ages beyond 5 years [169–172]. Future research could also examine the long-term effects and impacts of exposures at later ages in relation to the general variation in crop yield in subsistence farming populations, as currently research on these aspects is limited. Also, an examination could be undertaken of the possibility of non-linear effects of extreme crop yield deficit temporally (in specific years) and spatially (in specific areas/households). Non-linear analyses could also inform on the level of crop yield beyond which the yield may no longer be associated with nutritional and other health outcomes.

(iii) Modelling future impacts

The improved evidence base relating to the exposure–response associations and their meta-analytical estimates could be used to model the future burden attributable to crop yield variation under different scenarios of climate change and development. Chapter 6 examined only one of the climate change trajectories (which is highly uncertain), assuming all other changes constant (an unlikely assumption). Further modelling studies of the full range of health impacts of future crop yield variation are required under other climate change scenarios combined with scenarios of local socio-economic development. Impact modelling for other climate change scenarios may require the use of process based crop yield modelling instead of the statistical crop models (used in this thesis), which are less appropriate for projecting crop yield in weather conditions different from those that the models were calibrated on.

The HDSS sites located in the areas vulnerable to negative effects of climate change on crop yields and populated by subsistence farming populations could also constitute hotspots for monitoring future climate change impacts [173,174]. This could allow for the calibration of local future impact models and provide an insight into any progress made on reducing the nutritional impacts of climate change. Additionally, the empirical exposure–response functions identified for subsistence farming populations could be used as an input into the global models of climate change impacts on undernutrition and mortality [175]. Future modelling studies could also attempt to account for the effects of weather variation not only on changes in the harvest quantity but also its nutritional quality [176].

(iv) Understanding the underlying causal processes and vulnerability

It was beyond the scope of this thesis to examine any specific processes through which low crop yields might lead to increased child undernutrition and mortality. These associations may operate through changes in household food production and individual food intake, through household income, food prices and purchases, through rates of infectious diseases and health care expenses/utilization, and through other processes [107]. It is particularly important to identify factors that may intensify or diminish these impacts, as these may inform the design of the necessary interventions as well as long-term developmental and adaptation strategies.

Research on causal processes and modifying factors could follow mixed methods design with qualitative research results defining quantitative hypotheses. Qualitative methodology could be used to understand the underlying processes that render households and children vulnerable to crop yield deficits as well as existing and potential preventative, adaptive, and coping strategies, any constraining and facilitating factors, and any unused capacity for improvement. Qualitative findings could inform hypotheses for more specific quantitative mediation and modification analyses. Such analyses may require new quantitative data collection with sufficiently large sample sizes. As shown in Chapter 4, the dataset of 975 subjects was insufficient to detect differences in the association by sex.

Further research should also explore the possibility of analysing the association of outcome data in relation to more spatially disaggregated exposure data, e.g., household level *year-to-year* variation in crop yield. Methods of household level crop yield estimation using satellite data for analyses in relation to child nutritional status have been successfully piloted in Burkina Faso [121]. In future research, such approaches could be used on a greater scale for analysis and monitoring purposes. Such analyses could help to uncover differences in household level vulnerability to the risks of annual crop yield reductions.

(v) Identifying solutions

If further studies contribute a weight of evidence for the interpretation of the negative health and nutrition effects of crop yield reductions as causal, further research would be needed to design and evaluate possible strategies for mitigating the risk and protecting health in the susceptible populations. Design of such strategies could be informed by evidence of underlying causal processes and effect modifiers. To ensure stakeholder buy in, solutions could be co-designed with relevant stakeholders, including local, national, and international policy-makers from the relevant authorities (e.g., agricultural, health, climate change, food security, and development authorities) and community representatives. Co-design could be achieved through participative workshops, where current and future impact estimates, underlying causal processes, possible areas for interventions (e.g., household-level early warning systems, agricultural insurance schemes) and long-term improvement strategies (e.g., health care system strengthening, adaptation of drought resistant crop varieties) are discussed with stakeholders in terms of the feasibility, preferences, and any political, economic, and social barriers to the solution design and implementation. The identified solutions could then be piloted and evaluated through epidemiological monitoring, simulation modelling of altered health impact, as well as the evaluation of processes, outcomes, cost-effectiveness, and impact. Results of such evaluation could again be presented to the policy-makers and other stakeholders to encourage their consideration of initiatives and policies for the reduction of health and nutrition risks of crop yield variation.

7.6. Policy implications

Policy implications in part depend on the degree to which the associations reported in my thesis reflect causal associations. While my results are consistent with broader published literature, the evidence base is far from conclusive. Nonetheless, it is likely that they reflect causal influences, and hence, there are important implications for policy.

The reduction of high levels of child undernutrition and mortality has been an important policy objective in such low-income countries as Burkina Faso. Averaged across all years of MUAC measurement availability (2009–2012) in the Nouna HDSS area, the prevalence of child acute undernutrition was nearly *critical*, as per the WHO classification [115]. Key findings of this thesis, if interpreted as reflecting causal associations, suggested that low crop harvest levels pose an observable risk for child undernutrition and its associated adverse health outcomes. Even small annual yield reductions from period average levels were associated with appreciable increases in child mortality. Hence, it appears that child undernutrition and mortality in this setting could in part be reduced by addressing the risk posed by low household crop harvests and annual yield reductions.

My estimates of the monetary value of the child mortality impact of annual crop yield reductions observed in the past exceeded the cost of grain required to compensate the harvest deficit. This finding suggests that there could be value in considering the development and implementation of strategies to protect against the effects of low crop yields. There are various approaches to further enhance cost-effectiveness of support strategies, including targeted support. The findings of non-linear shape of the association of MUAC and household crop harvest suggested that the risk of child undernutrition could be greatest in households with the lowest harvest levels. Household crop harvest could be used as a monitoring measure to identify the most vulnerable households for the provision of targeted support. The feasibility of crop harvest monitoring that could potentially be suitable for such purposes has been demonstrated in the Nouna HDSS area through the use of satellite imagery [177].

It is therefore important to consider possible strategies of addressing the risks of low household harvests and annual yields. Wider literature suggests possibly relevant strategies ranging from food and supplement distribution [178,179], conditional cash transfers [180,181], food-for-work programmes [182], crop insurance schemes [183–185] or other support. It was beyond the scope of this thesis to examine what form appropriate strategies or interventions could be take in this setting. However, as the weather-crop yield model showed, low crop yields in the Nouna HDSS area are largely attributable to the vagaries of the weather. This suggests that particular efforts targeted specifically at ameliorating the effects of the weather on crop production should be considered (e.g., use of drought resistant seeds, improved irrigation, early warning systems).

Furthermore, estimates in this thesis suggested that the burden of child mortality attributed to crop yield reductions in the Nouna HDSS could increase under future climate change, assuming all other conditions remain the same. Although the estimated magnitude of such increase was not dramatic, these estimates pertain to the most conservative (and possibly the least realistic) climate change scenario. Under more realistic climate change scenarios, increase in these impacts could be more dramatic. Hence, the estimates presented in this thesis add to the case for accelerating climate change mitigation efforts aiming to keep global warming to the 1.5 °C increase by the end of the 21st century.

7.7. Conclusion

This thesis examined crop yield variation as an epidemiological risk factor for child undernutrition and mortality in a subsistence farming population in rural Burkina Faso in the context of weather variability. The findings of this research provided an initial contribution to address the gap in the empirical evidence of this risk factor by identifying associations along an indirect pathway of climate change impacts on human health, hypothesised to operate through crop productivity and nutrition.

The results demonstrated that household crop harvest could be an important determinant of child nutritional status, measured by MUAC, in the Nouna HDSS area. In a year of average conditions of agricultural productivity, child MUAC was associated with differences in crop harvest in households that produced <3,000 kcal/ae/d. Further results demonstrated that child survival was appreciably worse in children born in years with low yield. Additionally, the evidence of an association between annual crop yield and child MUAC and the association between child MUAC and survival suggested that poorer nutritional status may in part explain the lower survival among those children who were born in years of low yield.

Finally, this thesis provided estimates of the magnitude of the child mortality impact attributable to crop yield deficit in the Nouna HDSS area in the recent past, which were largely related to unfavourable weather variations. The monetised equivalent of this impact exceeded the cost of grain required to cover the corresponding harvest deficit, suggesting that there might be value in addressing such deficits and their associated health risks. The thesis findings also added to the case for climate change mitigation, as the attributed child mortality impact was projected to increase even under the weather conditions of 1.5 °C global warming scenario, other factors assumed constant.

This thesis contributed to the empirical evidence of crop yield as an epidemiological risk factor for child undernutrition and mortality in the context of weather variation. Impact estimates suggested that this risk factor is of appreciable importance for one subsistence farming population of sub-Saharan Africa, calling for consideration of suitable response strategies. Although the evidence in this thesis pertained to a single population, similar impacts could be identified in comparable subsistence farming populations relying on rain-fed agriculture and subjected to unfavourable climatic changes.

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Annexes

Annex 1: Ethics approval from the London School of Hygiene and Tropical Medicine Observational Ethics Committee

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Observational / Interventions Research Ethics Committee

Miss Kristine Belesova
Research Degree Student
PHP
LSHTM

4 November 2014

Dear Miss Belesova,

Study Title: Children's Nutrition and Nutrition-Related Health Outcomes during Periods of Drought and Food Stress in Burkina Faso

LSHTM Ethics Ref: 8624

Thank you for your letter of 31 October 2014, responding to the Observational Committee's request for further information on the above research and submitting revised documentation.

The further information has been considered on behalf of the Committee by the Chair.

Confirmation of ethical opinion

On behalf of the Committee, I am pleased to confirm a favourable ethical opinion for the above research on the basis described in the application form, protocol and supporting documentation as revised, subject to the conditions specified below.

Conditions of the favourable opinion

Approval is dependent on local ethical approval having been received, where relevant.

Approved documents

The final list of documents reviewed and approved by the Committee is as follows:

Document Type	File Name	Date	Version
Protocol / Proposal	Upgrading_Document_Kristine_14092014_RevEth.pdf	28/09/2014	v.1
Protocol / Proposal	Interview_topic_guide.docx	30/09/2014	v.1
Information Sheet	Consent_form_HH_Head.docx	30/09/2014	v.1
Information Sheet	Information_sheet_HH_head.docx	30/10/2014	v.2

After ethical review

Any subsequent changes to the application must be submitted to the Committee via an Amendment form on the ethics online applications website. The Principal Investigator is reminded that all studies are also required to notify the ethics committee of any serious adverse events which occur during the project via an Adverse Event form on the ethics online applications website. At the end of the study, please notify the committee via an End of Study form on the ethics online applications website. Ethics online applications website link: http://leo.lshtm.ac.uk

Yours sincerely,

[redacted]

Professor John DH Porter
Chair

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http://www.lshtm.ac.uk/ethics/

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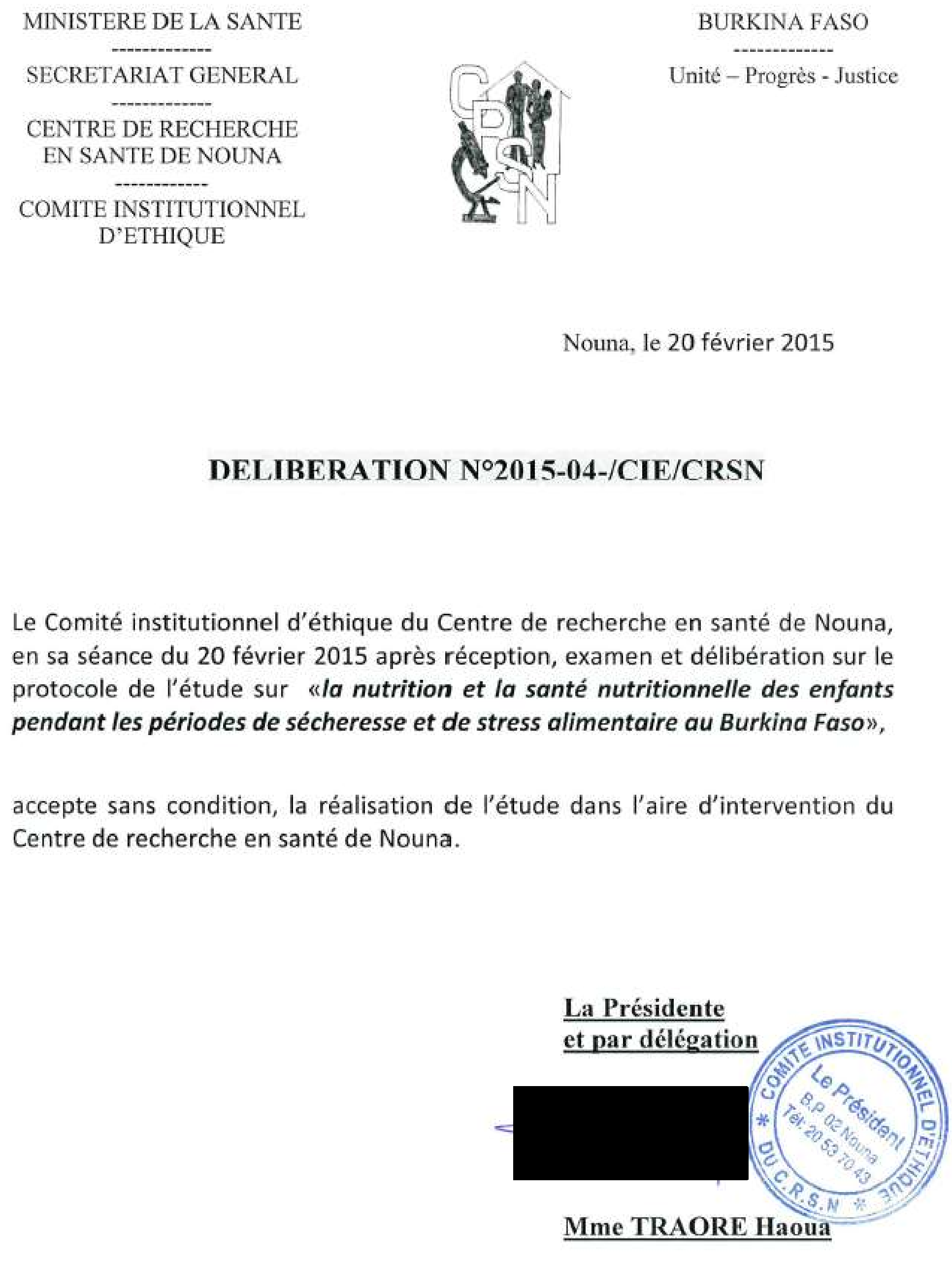
Annex 2: Ethics approval from the Comité Institutionnel d’Ethique du Centre de Recherche en Santé de Nouna



MINISTERE DE LA SANTE

SECRETARIAT GENERAL

CENTRE DE RECHERCHE
EN SANTE DE NOUNA

COMITE INSTITUTIONNEL
D’ETHIQUE

BURKINA FASO

Unité – Progrès - Justice

Nouna, le 20 février 2015

DELIBERATION N°2015-04-/CIE/CRSN

Le Comité institutionnel d’éthique du Centre de recherche en santé de Nouna, en sa séance du 20 février 2015 après réception, examen et délibération sur le protocole de l’étude sur «***la nutrition et la santé nutritionnelle des enfants pendant les périodes de sécheresse et de stress alimentaire au Burkina Faso***»,

accepte sans condition, la réalisation de l’étude dans l’aire d’intervention du Centre de recherche en santé de Nouna.

La Présidente
et par délégation

[redacted]

Le Président

Mme TRAORE Haoua

Annex 3: Supplementary material for Paper 1 *Systematic literature review*

Table 9—1. Example of the full search strategy, used in Medline.

Search	Medline
#1 Low- and middle- income country terms	(((developing or less* developed or under developed or underdeveloped or middle income or low* income) adj (economy or economies)).ti,ab.) OR (((developing or less* developed or under developed or underdeveloped or middle income or low* income or underserved or under served or deprived or poor*) adj (countr* or nation? or population? or world)).ti,ab.) OR ((low* adj (gdp or gnp or gross domestic or gross national)).ti,ab.) OR ((low adj3 middle adj3 countr*).ti,ab.) OR ((lmic or lmics or third world or lami countr*).ti,ab.) OR (transitional countr*.ti,ab.) OR (cambodia OR (north korea or (democratic people* republic adj2 korea)) OR (myanmar or burma) OR fiji OR indonesia OR Kiribati OR (laos or (lao adj1 democratic republic)) OR marshall island* OR mongolia OR Papua New Guinea OR Philippines OR samoa OR Solomon Islands OR Timor-Leste OR tonga OR Vanuatu OR Vietnam OR american samoa OR china OR malaysia OR Palau OR Thailand OR Tuvalu OR (kyrgyzstan or kyrgyz republic or kirghizia or kirghiz) OR (tajikistan or tadzhik or tadzhikistan or tajikistan) OR Albania OR Armenia OR Kosovo OR Moldova OR Ukraine OR Uzbekistan OR Azerbaijan OR (belarus or byelarus or belorussia) OR bosnia OR Bulgaria OR (Kazakhstan or kazakh) OR Latvia OR Lithuania OR Macedonia OR Montenegro OR Romania OR (Russia or Russian Federation) OR USSR OR serbia OR turkey not animal/ OR Turkmenistan OR Haiti OR Belize OR Bolivia OR El Salvador OR Guatemala OR Guyana OR Honduras OR Nicaragua OR Paraguay OR (Antigua or Barbuda) OR Argentina OR Brazil OR Chile OR Colombia OR Costa Rica OR Cuba OR Dominica OR Dominican Republic OR Ecuador OR Grenada OR Jamaica OR Mexico OR Panama OR Peru OR (St Lucia or Saint Lucia) OR Grenadines OR Suriname OR Uruguay OR Venezuela OR (Djibouti or French Somaliland) OR Egypt OR Iraq OR Morocco OR (Syria or Syrian Arab Republic) OR Gaza OR Yemen OR Algeria OR Iran OR Jordan OR Lebanon OR Libya OR Tunisia OR Afghanistan OR Bangladesh OR Nepal OR Bhutan OR India OR Pakistan OR Sri Lanka OR Maldives OR (Benin or Dahomey) OR (Burkina Faso or Burkina Fasso or Upper Volta) OR Burundi OR (Central African Republic or Ubangi-Shari) OR Chad OR (Comoros or Comoro Islands or Mayotte or Iles Comores) OR ((democratic republic adj2 congo) or belgian congo or zaire) OR Eritrea OR Ethiopia OR Gambia OR (Guinea not (New Guinea or Guinea Pig* or Guinea Fowl)) OR (Guinea-Bissau or Portuguese Guinea) OR Kenya OR Liberia OR (Madagascar or Malagasy Republic) OR (Malawi or Nyasaland) OR Mali OR Mauritania OR (Mozambique or Portuguese East Africa) OR (Niger not (Aspergillus or Peptococcus or Schizothorax or Cruciferae or Gobius or Lasius or Agelastes or Melanosuchus or radish or Parastromateus or Orius or Apergillus or Parastromateus or Stomoxys)) OR (Rwanda or Ruanda) OR Sierra Leone OR Somalia OR (Tanzania or Zanzibar) OR (Togo or Togolese Republic) OR Uganda OR (Zimbabwe or Rhodesia) OR Cameroon OR Cape Verde OR (congo not ((democratic republic adj3 congo) or congo red or crimean-congo)) OR (Cote d'Ivoire or Ivory Coast) OR (Ghana or Gold Coast) OR (Lesotho or Basutoland) OR

	Nigeria OR (sao tome adj2 principe) OR Senegal OR Sudan OR Swaziland OR (Zambia or Northern Rhodesia) OR Angola OR (Botswana or Bechuanaland or Kalahari) OR (Gabon or Gabonese Republic) OR (Mauritius or Agalega Islands) OR Namibia OR Seychelles OR South Africa.mp.) OR Developing Countries/ OR Cambodia/ OR "Democratic People's Republic of Korea"/ OR Myanmar/ OR Fiji/ OR Indonesia/ OR Micronesia/ OR Laos/ OR Mongolia/ OR Papua New Guinea/ OR Philippines/ OR samoa/ or "independent state of samoa"/ OR Melanesia/ OR Tonga/ OR Vanuatu/ OR Vietnam/ OR American Samoa/ OR exp China/ OR Malaysia/ OR Palau/ OR Thailand/ OR Kyrgyzstan/ OR Tajikistan/ OR Albania/ OR Armenia/ OR "Georgia (Republic)"/ OR Yugoslavia/ OR Moldova/ OR Ukraine/ OR Uzbekistan/ OR Azerbaijan/ OR "Republic of Belarus"/ OR Bosnia-Herzegovina/ OR Bulgaria/ OR Kazakhstan/ OR Latvia/ OR Lithuania/ OR "Macedonia (Republic)"/ OR Montenegro/ OR Romania/ OR exp Russia/ OR USSR/ OR Serbia/ OR Turkey/ OR Turkmenistan/ OR Haiti/ OR Belize/ OR Bolivia/ OR El Salvador/ OR Guatemala/ OR Guyana/ OR Honduras/ OR Nicaragua/ OR Paraguay/ OR "Antigua and Barbuda"/ OR Argentina/ OR Brazil/ OR Chile/ OR Colombia/ OR Costa Rica/ OR Cuba/ OR Dominica/ OR Dominican Republic/ OR Ecuador/ OR Grenada/ OR Jamaica/ OR Mexico/ OR exp Panama/ OR Peru/ OR Saint Lucia/ OR "Saint Vincent and the Grenadines"/ OR Suriname/ OR Uruguay/ OR Venezuela/ OR Djibouti/ OR Egypt/ OR Iraq/ OR Morocco/ OR Syria/ OR Yemen/ OR Algeria/ OR Iran/ OR Jordan/ OR Lebanon/ OR Libya/ OR Tunisia/ OR Afghanistan/ OR Bangladesh/ OR Nepal/ OR Bhutan/ OR exp India/ OR Pakistan/ OR Sri Lanka/ OR Indian Ocean Islands/ OR Benin/ OR Burkina Faso/ OR Burundi/ OR Central African Republic/ OR Chad/ OR Comoros/ OR "Democratic Republic of the Congo"/ OR Eritrea/ OR Ethiopia/ OR Gambia/ OR Guinea/ OR Guinea-Bissau/ OR Kenya/ OR Liberia/ OR Madagascar/ OR Malawi/ OR Mali/ OR Mauritania/ OR Mozambique/ OR Niger/ OR Rwanda/ OR Sierra Leone/ OR Somalia/ OR Tanzania/ OR Togo/ OR Uganda/ OR Zimbabwe/ OR Cameroon/ OR Cape Verde/ OR Congo/ OR Cote d'Ivoire/ OR Ghana/ OR Lesotho/ OR Nigeria/ OR Atlantic Islands/ OR Senegal/ OR Sudan/ OR Swaziland/ OR Zambia/ OR Angola/ OR Botswana/ OR Gabon/ OR Mauritius/ OR Namibia/ OR Seychelles/ OR South Africa/
#2 Outcome terms	((malnu* or undernu* or under-nu* or under-feeding or stunt* or "low birth-weight*" or "low birth weight*" or emanciat* or famine or starv* or "suboptimal* breastfe*" or "poor nutrition" or "food shortage*" or wast* or under-weight* or under-norish* or "calorie* availab*" or "nutrient deficienc*" or "protein definienc*" or "calorie deficienc*" or "micronutrient deficienc*" or hunger or marasmus or kwashiorkor or "protein energy malnutrition" or cachexia or immunosupress* or hypoplasi* or ((protein* or nutrient* or microelement*) adj3 (loss or intake))).mp.) OR exp Protein-Energy Malnutrition/ or exp Malnutrition/) OR (exp Caloric Restriction/ or exp Body Weight/ or exp Food Deprivation/ or exp Energy Intake/ or exp Deficiency Diseases/) OR (exp Growth Disorders/) OR (exp Starvation/) OR (exp Nutrition Disorders/ or exp Nutritional Status/) OR (exp Food Deprivation/) OR (exp Wasting Syndrome/ or exp Wasting Disease, Chronic/) OR (exp Thinness/) OR (exp Energy Intake/) OR (exp Hunger/) OR (exp Kwashiorkor/) OR (exp Cachexia/) OR (exp Immunosuppression/) OR (exp Focal Dermal Hypoplasia/ or exp Dental Enamel Hypoplasia/) OR (exp Nutritional Status/ or exp Energy Intake/ or exp Nutrition) OR (exp Nutrition Assessment/) OR (exp Nutrition Surveys/) OR (exp Diet/) OR (exp Anemia, Iron-Deficiency/) OR (exp Anemia, Hypochromic/) OR (exp Vitamin A Deficiency/) OR (exp Folic Acid Deficiency/) OR (exp Deficiency Diseases/) OR (exp

	Protein Deficiency/) OR (exp Riboflavin Deficiency/) OR (exp Obesity/) OR (exp Metabolic Diseases/) OR (exp Metabolic Syndrome X/) OR (exp Nutrition Assessment/) OR (exp Enteral Nutrition/) OR (exp Nutrition Disorders/) OR (exp Parenteral Nutrition/) OR (exp Parenteral Nutrition, Home Total/) OR (exp Parenteral Nutrition Solutions/) OR (exp Fetal Nutrition Disorders/) OR (exp Child Nutrition Disorders/) OR (exp Nutrition Surveys/) OR (exp Parenteral Nutrition, Home/) OR (exp Parenteral Nutrition, Total/) OR (exp Infant Nutrition Disorders/)
#3 Exposure terms	((((Climat* or weather) adj4 (chang* or variab* or extreme*)) or (global adj2 warming) or ((greenhouse or "green house") adj2 effect)).mp.) OR (exp Climate Change/) OR (exp Global Warming/) OR (exp Greenhouse Effect/) OR ((drought* or arid* or dessicat* or (dry adj3 (spell* or condition* or weather* or period* or season*)) or rainless* or rain-less* or "water depriv*" or "water stress*" or ((lack or low* or chang*) adj3 (rain* or percipitat*)) or desertificat*).mp.) OR (exp Drought/) OR (exp Desert Climate/) OR (exp Desiccation/) OR (exp Seasons/)
#4	**#1 AND #2 AND #3**
#5 Articles reporting empirical observational human studies, and published in English	limit **#4** to (english language and humans and (case reports or classical article or comparative study or "corrected and republished article" or duplicate publication or editorial or evaluation studies or introductory journal article or journal article or multicenter study or "review" or "scientific integrity review" or systematic reviews or technical report))
#6 Studies published over 1990–2016	limit **#5** to yr="1990–Current"

Table 9—2. Study inclusion and exclusion criteria.

	Inclusion criteria	Exclusion criteria
Literature type	- Peer-reviewed papers reporting empirical observational studies	- Commentaries, editorials, literature reviews - News reports and book chapters - Non peer-reviewed literature
Population	- Human	- Non-human
	- Children <5 years of age	- People ≥5 years of age
Exposure-outcome link	- The outcome measured in relation to a drought event(-s)	- The outcome was measured in a population in a drought-prone area without a reference to a specific drought event(-s) - The outcome measured in a population that has been displaced by droughts in the past without a reference to a specific drought event - The outcome was measured in a population exposed to a dry (e.g., desert) environment, not a specific drought event(-s) - The outcome was examined in relation to general variability in vegetation productivity, weather or agricultural production, but not droughts (understood as relatively extreme events/conditions)
Outcome measure	- Measures of child nutritional status	- Other health indicators (e.g., all-cause or cause-specific mortality (including, nutrition as the cause), infectious diseases) - Measures of food security, undernourishment (insufficient supply of food), and food intake
Country of study	- Low- and middle-income countries as classified by the World Bank in April, 2013	- High-income countries as classified by the World Bank in April, 2013
Year of publication	- 1990 (incl.)–19 August 2016	- Prior to 1990
Language of publication	- English	- Languages other than English

Note 9–1. Instructions for the Risk of Bias Assessment in individual studies, modified from Johnson *et al* (2014) and Johnson *et al* (2016) [1–3].

1. Exposure assessment: *Were exposure assessment methods robust?*

1.1. Criteria for a judgement '*low risk of bias*'

'Low risk of bias' judged when drought exposure in the exposed population and absence of such exposure in the control population/time was:

- determined by authors of the study using data on a direct proxy indicator of drought (e.g., rainfall, agricultural production),
- supported by references to material that reports such proxy indicator of drought.

1.2. Criteria for a judgement '*probably low risk of bias*'

There is insufficient information on exposure assessment methods to permit a judgment '*low risk of bias*', but there is indirect evidence suggesting that methods were robust, as described by the criteria for a judgment '*low risk of bias*'.

1.3. Criteria for a judgement '*probably high risk of bias*'

There is insufficient information about the exposure assessment methods to permit a judgment '*high risk of bias'*, but there is indirect evidence suggesting that methods were not robust, as described by the criteria for a judgment '*high risk of bias*'.

1.4. Criteria for a judgement '*high risk of bias*'

'High risk of bias' judged when drought exposure in the exposed population and/or absence of such exposure in the control population/time was:

- reported by the study participants retrospectively, which is subject to recall bias,
- determined using a measure that was likely to introduce bias,
- claimed without supporting information such as data on a proxy indicator of drought,
- not mentioned for the control population/time.

1.5. Criteria for a judgement '*not applicable*'

There is evidence that exposure assessment is not capable of introducing risk of bias in the study.

2. Outcome assessment: *Where the outcome assessment methods robust?*

2.1. Criteria for a judgement '*low risk of bias*'

'Low risk of bias' judged in the outcome assessment when the following two criteria were met:

- study used an appropriate measure of nutritional outcome (e.g., weight/height index instead of just weight of children of different ages),
- study used a standard outcome definition (e.g., moderate acute undernutrition defined in cases when an individual's weight-for-height index was <-2 Z scores).

Studies with cross-sectional designs were judged '*low risk of bias*', when anthropometric indices were assessed against the World Health Organisation (WHO) Multicentre Growth Reference Study standards for child growth and development. These standards demonstrate the ideal growth possible in young children [4,5].

2.2. Criteria for a judgement '*probably low risk of bias*'

There is insufficient information on outcome assessment methods to permit a judgment '*low risk of bias*', but there is indirect evidence suggesting that methods were robust.

2.3. Criteria for a judgement '*probably high risk of bias*'

There is insufficient information on outcome assessment methods to permit a judgment '*high risk of bias*', but there is indirect evidence suggesting that methods were not robust. Studies were also judged at '*probably high risk of bias*', when cross-sectional studies assessed anthropometric indices against the National Centre for Health Statistics (NCHS) growth reference. The use of this reference is shown to underestimate the level of child undernutrition [4,5].

2.4. Criteria for a judgement '*high risk of bias*'

'*High risk of bias'* judged in the outcome assessment, if the study:

- used less direct outcome measures (e.g., weight as opposed to weight/height index),
- used other than standard outcome definition,
- lacked information on how the outcome information was obtained.

2.5. Criteria for a judgement '*not applicable*'

There is evidence that outcome assessment is not capable of introducing risk of bias in the study.

3. Recruitment and sampling strategy: *Was the strategy for sampling and recruiting participants consistent across study groups, representing the study population?*

3.1. Criteria for a judgement '*low risk of bias*'

'*Low risk of bias'* judged in the sampling and recruitment strategy, if:

- study subjects were sampled and recruited so that the sample is representative of the study population,
- in a study using control areas/time periods, there was no difference in the selection strategy of subjects among the exposed and unexposed and no difference in the underlying characteristics of these groups.

3.2. Criteria for a judgement '*probably low risk of bias*'

There is insufficient information about participant selection to permit a judgment '*low risk of bias*', but there is indirect evidence suggesting that participant recruitment and sampling process was consistent, as described by the criteria for a judgment '*low risk of bias*'.

3.3. Criteria for a judgement '*probably high risk of bias*'

There is insufficient information about participant selection to permit a judgment '*high risk of bias*', but there is indirect evidence suggesting that participant recruitment or sampling was as described by the criteria for a judgment '*high risk of bias*'.

3.4. Criteria for a judgement '*high risk of bias*'

'*High risk of bias*' in the sampling and recruitment strategy judged, if:

- study subjects were sampled and recruited so that the sample was not representative of the study population in the drought-affected area,
- in studies using control areas/time periods, there were differences in the selection of subjects among the exposed and unexposed and difference in the underlying characteristics of these groups.

3.5. Criteria for a judgement '*not applicable*'

There is evidence that participant selection is not capable of introducing risk of bias in the study.

4. Blinding: *Was knowledge of the exposure groups adequately prevented during the study?*

4.1. Criteria for a judgement '*low risk of bias*'

'*Low risk of bias*' judged in relation to blinding, if:

- there was no blinding, but the review authors judge that the outcome and its measurement are not likely to be influenced by the lack of blinding,
- blinding of key study personnel ensured, and unlikely that blinding could have been broken,
- some key study personnel were not blinded, but outcome assessment was blinded and the non-blinding of others unlikely to introduce bias.

4.2. Criteria for a judgement '*probably low risk of bias*'

There is insufficient information about blinding to permit a judgment '*low risk of bias*', but there is indirect evidence suggesting that the study was adequately blinded, as described by the criteria for a judgment of '*low risk of bias*'.

4.3. Criteria for a judgement '*probably high risk of bias*'

There is insufficient information about blinding to permit a judgment of '*high risk of bias*', but there is indirect evidence suggesting that the study was not adequately blinded, as described by the criteria for a judgment '*high risk of bias*'.

4.4. Criteria for a judgement '*high risk of bias*'

'*High risk of bias*' judged in relation to blinding, if:

- there was no blinding or incomplete blinding, and the outcome or outcome measurement is likely to be influenced by the lack of blinding,
- blinding of key study personnel attempted, but likely that blinding could have been broken, or
- outcome assessment was blinded but some key study personnel were not blinded, which was likely to introduce bias.

4.5. Criteria for a judgement ‘*not applicable*’

There is evidence that blinding is not capable of introducing risk of bias in the study.

5. Confounding: *Was confounding adequately addressed?*

5.1. Criteria for a judgement ‘*low risk of bias*’

‘*Low risk of bias*’ judged if the study accounted (i.e., matched, stratified, multivariate analysis or otherwise statistically controlled) for important potential confounders, or reported that potential confounders were evaluated and omitted because their inclusion did not substantially affect the results.

5.2. Criteria for a judgement ‘*probably low risk of bias*’

The study accounted for most but not all the important potential confounders AND this lack of accounting is not expected to introduce substantial bias.

5.3. Criteria for a judgement ‘*probably high risk of bias*’

The study accounted for some but not all the important potential confounders AND this lack of accounting may have introduced substantial bias.

5.4. Criteria for a judgement ‘*high risk of bias*’

‘*High risk of bias*’ judged if the study did not account for or evaluate important potential confounders.

5.5. Criteria for a judgement ‘*not applicable*’

There is evidence that confounding is not capable of introducing risk of bias in the study. ‘*Not applicable*’ was also judged in relation to cross-sectional studies that provided a single prevalence estimate of undernutrition, without examining its statistical association with drought exposure.

6. Incomplete outcome data: *Were incomplete outcome data adequately addressed?*

6.1. Criteria for a judgement ‘*low risk of bias*’

‘*Low risk of bias*’ judged in relation to incomplete outcome data, if:

- there was no missing outcome data,
- reasons for missing outcome data were unlikely to be related to true outcome,
- missing outcome data balanced in numbers across exposure groups, with similar reasons for missing data across groups,
- for dichotomous outcome data, the proportion of missing outcomes compared with observed event risk was not sufficient to have a biologically relevant impact on the intervention effect estimate,
- for continuous outcome data, plausible effect size (difference in means or standardized difference in means) among missing outcomes was not sufficient to have a biologically relevant impact on the observed effect size,

- missing data have been imputed using appropriate methods.

6.2. Criteria for a judgement '*probably low risk of bias*'

There is insufficient information about incomplete outcome data to permit a judgment '*low risk of bias*', but there is indirect evidence suggesting incomplete outcome data was adequately addressed, as described by the criteria for a judgment '*low risk of bias*'.

6.3. Criteria for a judgement '*probably high risk of bias*'

There is insufficient information about incomplete outcome data to permit a judgment '*high risk of bias*', but there is indirect evidence suggesting incomplete outcome data was not adequately addressed, as described by the criteria for a judgment '*high risk of bias*'.

6.4. Criteria for a judgement '*high risk of bias*'

'*High risk of bias*' judged in relation to incomplete data, if:

- reason for missing outcome data were likely to be related to true outcome, with either imbalance in numbers or reasons for missing data across exposure groups,
- for dichotomous outcome data, the proportion of missing outcomes compared with observed event risk was sufficient to induce biologically relevant bias in intervention effect estimate,
- for continuous outcome data, plausible effect size (difference in means or standardized difference in means) among missing outcomes was sufficient to induce biologically relevant bias in the observed effect size,
- potentially inappropriate application of imputation.

6.5. Criteria for a judgement '*not applicable*'

There is evidence that incomplete outcome data is not capable of introducing risk of bias in the study.

7. Selective reporting: *Are reports of the study free of the suggestion of selective outcome reporting?*

7.1. Criteria for a judgement '*low risk of bias*'

All of the study's pre-specified (primary and secondary) outcomes, of interest to the review, outlined in the protocol, methods, abstract, and/or introduction have been reported in the pre-specified way.

7.2. Criteria for a judgement '*probably low risk of bias*'

There is insufficient information about selective outcome reporting to permit a judgment '*low risk of bias*', but there is indirect evidence suggesting that the study was free of selective reporting, as described by the criteria for a judgment '*low risk of bias*'.

7.3. Criteria for a judgement '*probably high risk of bias*'

There is insufficient information about selective outcome reporting to permit a judgment '*high risk of bias*', but there is indirect evidence suggesting that the study was not free of selective reporting, as described by the criteria for a judgment '*high risk of bias*'.

7.4. Criteria for a judgement ‘*high risk of bias*’

‘*High risk of bias*’ judged in relation to selective outcome reporting, if:

- not all of the study’s pre-specified primary outcomes (as outlined in the protocol, methods, abstract, and/or introduction) have been reported,
- one or more primary outcomes are reported using measurements, analysis methods or subsets of the data (e.g., subscales) that were not pre-specified,
- one or more of the reported primary outcomes were not pre-specified (unless clear justification for their reporting without pre-specification is provided, such as an unexpected effect).

7.5. Criteria for a judgement ‘*not applicable*’

There is evidence that selective outcome reporting is not capable of introducing risk of bias in the study.

8. Conflict of interest: *Was the study free of support from the study author or any other entity having a financial interest in exposures/ outcomes studied?*

8.1. Criteria for a judgement ‘*low risk of bias*’

‘*Low risk of bias*’ judged if the study did not receive support from any entity with financial interest in the study outcome, e.g.:

- funding source is limited to government or academic grants,
- staff affiliated with a company/government/non-governmental organisation (NGO) are not mentioned in the acknowledgements,
- authors were not employees of and not affiliated with a company/government/NGO with a financial interest in the outcome of the study, and there is no reason to believe a conflict of interest exists,
- company/government/NGO with a financial interest in the outcome of the study was not involved in the design, conduct, analysis, or reporting of the study and authors had complete access to the data,
- study authors make a claim denying conflicts of interest,
- study authors are not affiliated with companies/governments/NGOs with financial interest.

8.2. Criteria for a judgement ‘*probably low risk of bias*’

There is insufficient information to permit a judgment ‘*low risk of bias*’, but there is indirect evidence suggesting that the study was free of support from a company, study author, or other entity having a financial interest in the outcome of the study, as described by the criteria for ‘*low risk of bias*’. ‘*Probably low risk of bias*’ was also judged when a government or NGO was involved in the design, conduct, and analysis directly or through any other involvement of its employees.

8.3. Criteria for a judgement ‘*probably high risk of bias*’

There is insufficient information to permit a judgment ‘*high risk of bias*’, but there is indirect evidence suggesting that the study was not free of support from a company, study author, or other entity having a financial interest in the outcome of the study, as described by the criteria for a judgment ‘*high risk of bias*’.

8.4. Criteria for a judgement '*high risk of bias*'

'*High risk of bias*' was judged if there was evidence that the study received support from the study author or any other entity having financial interest in the outcome of the study, e.g.:

- research funds,
- materials provided at no cost,
- writing services,
- author/staff from study was employee or otherwise affiliated with an entity with financial interest in the study outcome,
- an entity with financial interest in the study outcome limited author access to the data,
- an entity with financial interest in the study outcome was involved in the design, conduct, analysis, or reporting of the study,
- study authors claim a conflict of interest.

8.5. Criteria for a judgement '*not applicable*'

There is evidence that conflicts of interest are not capable of introducing risk of bias in the study.

9. Migration or survival bias: *Was the study free of migration and survival bias?*

9.1. Criteria for a judgement '*low risk of bias*'

'*Low risk of bias*' judged in relation to possible differences in migration and survival, related to the drought, if:

- the study authors provide reliable evidence that the risk of survival and migration bias was low,
- the study covered a large geographical area and outcome data was collected in the beginning of the drought (broadly, the first year of the drought).

9.2. Criteria for a judgement '*probably low risk of bias*'

'*Probably low risk of bias*' was judged if:

- the study covered a localized geographical area but outcome data was collected in the beginning of the drought (broadly, the first year of the drought),
- the study covered a large geographical area but the outcome data was collected towards the end of the drought or shortly after the drought.

Hence, there was probably a low risk of bias related to differences in the levels of migration and survival across groups with different levels of the risk of child undernutrition.

9.3. Criteria for a judgement '*probably high risk of bias*'

'*Probably high risk of bias*' was judged if the study covered a localized geographical area and outcome data was collected towards the end of the drought or shortly after the drought. Hence, there was '*probably high risk of bias*' related to differences in the levels of migration and survival across groups with different levels of the risk of child undernutrition. Focus on an exceptionally severe drought adds weight for this judgment when only one of the criteria is met.

9.4. Criteria for a judgement '*high risk of bias*'

High risk of bias was judged, if the authors of the study analysed and acknowledged a high risk of survival and/or migration bias.

9.5. Criteria for a judgement '*not applicable*'

There is evidence that migration and survival are not capable of introducing risk of bias in the study.

10. Other bias: *Was the study apparently free of other problems that could put it at a risk of bias?*

10.1. Criteria for a judgement '*low risk of bias*'

The study appears to be free of other sources of bias.

10.2. Criteria for a judgement '*probably low risk of bias*'

There is insufficient information to permit a judgment '*low risk of bias*', but there is indirect evidence suggesting that the study was free of other threats to validity.

10.3. Criteria for a judgement '*probably high risk of bias*'

There is evidence that other potential threats to validity are capable of introducing risk of bias.

10.4. Criteria for a judgement '*high risk of bias*'

There is at least one important risk of bias. For example, the study:

- had a potential source of bias related to the specific study design used,
- had extreme imbalance of characteristics among exposure groups; or had differential surveillance for outcome between exposure groups or between exposed/unexposed groups,
- the conduct of the study is affected by interim results (e.g., recruiting additional participants from a subgroup showing greater or lesser effect),
- an insensitive instrument is used to measure outcomes (which can lead to underestimation of both beneficial and harmful effects),
- selective reporting of subgroups,
- has been claimed to have been fraudulent,
- had some other problem.

10.5. Criteria for a judgement '*not applicable*'

There is evidence that other sources of bias are not capable of introducing risk of bias in the study.

Table 9—3. Reasons for study exclusion at the stage of the full text review.

Reason for exclusion	Studies (Author, year)
Not examining impact of drought	Alemu and Lindtjørn, 1997 [6]; CDC, 1990 [7]; CDC, 1992 [8]; Datar *et al*, 2013 [9]; Hagos *et al*, 2014 [10]; Hall *et al*, 2011 [11]; Kinyoki *et al*, 2015 [12]; Kismul *et al*, 2014 [13]; Mason *et al*, 2012 [14]; Thomas *et al*, 2013 [15]; Ross *et al*, 1990 [16]; Rowhani *et al*, 2011 [17]; Santana *et al*, 2002 [18]; Shively *et al*, 2015 [19]; Spiegel *et al*, 2004 [20]; Suk *et al*, 2016 [21]; Sassi, 2015 [22]; Unknown, 2012 [23]; Westerterp-Plantenga, 1999 [24]; Yamano *et al*, 2005 [25]
Not reporting nutritional outcomes	Bangs and Subianto, 1999 [26]; Bidinger *et al*, 1991 [27]; Burns *et al*, 2014 [28]; Chantarat *et al*, 2007 [29]; Clifford *et al*, 2010 [30]; Devereux and Naeraa, 2014 [31]; Ezra, 2001 [32]; Foster, 1993 [33]; Khogali, 1991 [34]; Kidane, 1990 [35]; Loevinsohn, 2015 [36]; Macassa *et al*, 2003 [37]; Mukupo, 1994 [38]; Paul, 1998 [39]; Shi, 2011 [40]; Shukla, 2014 [41]; Sivakumar and Kerbart, 2014 [42]; Speranza *et al*, 2008 [43]; CDC, 2001 [44]
Not a peer-reviewed paper reporting empirical study results	Arnold, 1991 [45]; Cabrol, 2011 [46]; Green, 2016 [47]; Headey, 2012 [48]; Hide, 2000 [49]; Khan *et al*, 2015 [50]; Khera, 2008 [51]; Loewenberg, 2014 [52]; Maskalyk, 2002 [53]; Taye *et al*, 2010 [54]; Th *et al*, 2009 [55]; Tirado *et al*, 2012 [56]; UN ACC/SNC, 1997 [57]; Wakabi, 2006 [58]; Wakabi, 2009 [59]; World Bank, 2002 [60]; Webb and Braun, 1994 [61]; Thomson, 2001 [62]; Zarocostas, 2011 [63]
Not examining children under 5 years of age	Arlappa *et al*, 2009 [64]; Cheung *et al*, 2003 [65]; Christian *et al*, 1993 [66]; Desai *et al*, 1992 [67]; Emmelin *et al*, 2009 [68]; Ezra & Kiros, 2000 [69]; Hoddinott and Kinsey, 2000 [70]; Huang *et al*, 2010 [71]; Nathan *et al*, 1996 [72]; Nichlos *et al*, 2013 [73]; Singh *et al*, 2008 [74]
An earlier published version of an already included study	Singh *et al*, 2006 [75]
Not reporting nutritional outcomes measured in drought and non-drought conditions separately	Kennedy, 1992 [76]

Table 9—4. Risk of bias assessment summary for Arlappa *et al*, 2011 [79].

Source of bias	Rating	Support for the judgement
Exposure assessment	Probably low risk	Drought exposure justified by referring to a government declaration of drought in areas specific to the study population, which could be based on the assessment of appropriate indicators. However, article did not provide any reference to such assessment.
Outcome assessment	Probably high risk	Clinical signs (Bitot's spots) used to estimate the prevalence of vitamin A deficiency, a method that is suggested to underestimate the prevalence of vitamin A deficiency [77,78].
Sampling and recruitment strategy	Probably low risk	Random sampling used to collect nutritional outcome data in the drought-time survey. Information on the sampling strategy for non-drought time surveys was not separately explained, some indication that the same sampling approach could have been used. Recruitment strategy not reported.
Blinding	Probably high risk	No blinding measures mentioned, unlikely that any were taken, which could have introduced bias.
Confounding	High risk	No measures taken to control for confounding.
Incomplete outcome data	Probably low risk	Data completeness was not possible to assess at the district level, the report of results at a higher level of aggregation suggested no incomplete outcome data.
Selective reporting	Low risk	All pre-specified outcomes reported in a pre-specified way.
Conflict of interest	Probably low risk	Authors acknowledged involvement of staff from a governmental institution.
Migration or survival bias	Probably high risk	Localized, severely affected areas were examined, which suggests that the study results could have been subjected to survival/migration bias. No measures were described as undertaken to address such bias.
Other bias	Low risk	No other potential biases suspected.

Table 9—5. Risk of bias assessment summary for Assefa *et al*, 2001 [80].

Source of bias	Rating	Support for the judgement
Exposure assessment	Probably high risk	Relevant drought exposure data was presented at the country level, with no evidence for the exposure status in the study area. This could have introduced bias, as droughts tend not to affect large areas uniformly and some smaller areas may not be affected by a drought that is reported at the country level.
Outcome assessment	Probably high risk	Appropriate nutritional outcome measures used. However, anthropometric indices were assessed against the NCHS international growth reference, which does not represent ideal growth that is possible in young children [4,5], and therefore, could have led to bias in the prevalence estimates of child undernutrition.
Sampling and recruitment strategy	Probably low risk	Representative sampling strategy used, however 6 of the 50 villages were excluded from selection due to complicated access (remote location). Instances when sampled individuals refused to participate were addressed appropriately.
Blinding	Probably high risk	No blinding measures mentioned, unlikely that any were taken, thus, possibly introducing bias.
Confounding	Not applicable	The study was based on a single cross-sectional survey, providing data on nutritional outcome levels only during the drought.
Incomplete outcome data	Probably low risk	Small proportion (1%) of data were excluded from analysis due to poor measurement. We judged that this was probably unlikely to introduce bias, given the small fraction of the missing data.
Selective reporting	Low risk	All pre-specified outcomes reported in a pre-specified way.
Conflict of interest	Probably low risk	Authors affiliated with an NGO and governmental organisation.
Migration or survival bias	Probably high risk	Study conducted in a localized area with data collection towards the end of the drought, which suggests that the study results could have been subjected to survival/migration bias. No measures were described as undertaken to address such bias.
Other bias	Low risk	No other potential biases suspected.

Table 9—6. Risk of bias assessment summary for Block *et al*, 2003 [81].

Source of bias	Rating	Support for the judgement
Exposure assessment	High risk	Drought exposure supported by data on food prices and food consumption, which does not permit discerning between exposure to the drought and the concurrent financial crisis.
Outcome assessment	Probably low risk	Appropriate nutritional outcome measures used. The use of the NCHS international growth reference in the assessment of anthropometric indices was unlikely to introduce bias, as it was used consistently across exposure groups, and hence, was unlikely to introduce bias in the effect estimate. It was not clear how data on children's age was obtained.
Sampling and recruitment strategy	Probably low risk	Random sample representative of the study population was drawn. Recruitment strategy not reported.
Blinding	Probably high risk	No blinding measures mentioned, unlikely that any were taken, which could have introduced bias.
Confounding	High risk	Analyses were based on the time-age-cohort design, limiting confounding by secular changes in nutritional status over time (cohort), age, and time effects. However, the design did not permit discerning the effect of drought from the effect of the concurrent financial crisis.
Incomplete outcome data	Unclear	The reported information was not sufficient to determine completeness of the outcome data.
Selective reporting	Probably low risk	Most outcomes were pre-specified and reported in a pre-specified way, except for children's height and length, whose measurements were mentioned in the methods but neither specified in the abstract nor reported in the results.
Conflict of interest	Probably low risk	Acknowledged support of an NGO and government agency.
Migration or survival bias	Probably low risk	Study conducted in a localized study area examining effect of a drought that lasted for only one year, which thus, suggests *probably low risk of bias*. No measures were described as undertaken to prevent migration or survival bias.
Other bias	Low risk	No other potential biases suspected.

Table 9—7. Risk of bias assessment summary for Carnell & Guyon, 1990 [82].

Sources of bias	Rating	Support for the judgement
Exposure assessment	Probably high risk	Relevant drought exposure data was presented at the country level, with no evidence for the exposure status of the study area, which could have introduced bias, as droughts do tend not to affect large areas uniformly.
Outcome assessment	Probably high risk	Appropriate nutritional outcome measures used, however, anthropometric indices were assessed against the NCHS international growth reference [4,5], and therefore, could have led to bias in the prevalence estimates of child undernutrition.
Sampling and recruitment strategy	Probably low risk	Sample was representative of the study population. Recruitment strategy was not reported.
Blinding	Probably high risk	No blinding measures mentioned, unlikely that any were taken, which could have introduced bias.
Confounding	Not applicable	The study was based on a single cross-sectional survey, providing data on nutritional outcome level during the drought.
Incomplete outcome data	Low risk	No incomplete outcome data.
Selective reporting	Low risk	All pre-specified outcomes reported in a pre-specified way.
Conflict of interest	Probably low risk	Acknowledged involvement of an NGO in data collection.
Migration or survival bias	Probably high risk	Study conducted in a localized area with data collection two years after the start of the drought, which suggest that the study results could have been subjected to survival and migration bias. No measures were described as undertaken to address such bias.
Other bias	Low risk	No other potential biases suspected.

Table 9—8. Risk of bias assessment summary for CDC, 1991 [83].

Sources of bias	Rating	Support for the judgement
Exposure assessment	Unclear	Drought exposure stated by the authors with no justification or reference.
Outcome assessment	Probably high risk	Appropriate nutritional outcome measures used, however, anthropometric indices were assessed against the NCHS international growth reference which does not represent ideal growth that is possible in young children [4,5], and therefore, could have led to bias in the prevalence estimates of child undernutrition.
Sampling and recruitment strategy	Probably low risk	Random sample, representative of the study population. Recruitment strategy not reported.
Blinding	Probably high risk	No blinding measures mentioned, unlikely that any were taken, which could have introduced bias.
Confounding	Not applicable	The study was based on a single cross-sectional survey, providing data on nutritional outcome level during the drought.
Incomplete outcome data	Unclear	The reported information was not sufficient to determine completeness of the outcome data.
Selective reporting	Low risk	All pre-specified outcomes were reported in a pre-specified way.
Conflict of interest	Probably low risk	Reported the involvement of an NGO and government in the study.
Migration or survival bias	Probably low risk	Study was conducted in a localized area, suggesting *probably low risk of bias*. No measures were described as undertaken to prevent migration or survival bias.
Other bias	Low risk	No other potential biases suspected.

Table 9—9. Risk of bias assessment summary for Chotard *et al*, 2010 [84].

Sources of bias	Rating	Support for the judgement
Exposure assessment	Probably high risk	Missing values in the drought exposure index, corrections introduced using national level indicators (not specific to the areas where outcome data was collected), possibly introducing bias.
Outcome assessment	Probably low risk	Outcome data was compiled from different nutritional surveys, which used different measures of child wasting. Authors assumed that Global Acute Malnutrition (GAM) (weight-for-height index <2 Standard Deviations (SD) + oedema; used in 8 out of 905 datasets with mean oedema prevalence of 0.8%, ranging from 0% to 2.2%) is equivalent to weight-for-height index <2SD (used in remaining datasets). This assumption may have introduced some bias in analyses in relation to drought exposure. However, such bias would be low, considering the low prevalence of oedema and few surveys using GAM.
Sampling and recruitment strategy	Probably low risk	Representative samples selected, using standard and largely consistent sampling methods. Recruitment strategy not reported.
Blinding	Probably high risk	No blinding measures mentioned, unlikely that any were taken, which could have introduced bias.
Confounding	Probably high risk	Analyses were controlled for season and livelihood type, other possible major confounders not addressed.
Incomplete outcome data	Low risk	Surveys with incomplete data were excluded from analysis.
Selective reporting	Low risk	All pre-specified outcomes reported in a pre-specified way.
Conflict of interest	Probably low risk	Reported the involvement of NGO staff.
Migration or survival bias	Probably high risk	Large proportion of the study population were pastoralists, where high migration rates are expected in response to events such as droughts. No measures were described as undertaken to prevent migration or survival bias.
Other bias	Low risk	No other potential biases suspected.

Table 9—10. Risk of bias assessment summary for De Waal *et al*, 2006 [85].

Sources of bias	Rating	Support for the judgement
Exposure assessment	Probably low risk	Exposure ascertained at the level of the study population with appropriate references. No explicit ascertainment of the absence of exposure in the non-drought time, but some indication present.
Outcome assessment	Unclear	Lack of information on how the anthropometric index of the outcome measure was calculated.
Sampling and recruitment strategy	Probably low risk	Representative sample of the drought-affected population selected.[1] Recruitment strategy not reported.
Blinding	Probably high risk	No blinding measures mentioned, unlikely that any were taken, which could have introduced bias.
Confounding	Not applicable	The study was based on a single cross-sectional survey, providing data on nutritional outcome level during the drought.
Incomplete outcome data	Unclear	The reported information was not sufficient to determine completeness of the outcome data.
Selective reporting	Probably low risk	Nutritional outcomes were pre-specified in the abstract but not explicitly mentioned in the methods section of the paper. However, sufficient detail was provided on the survey, which these data were derived from. As nutritional outcomes were not the main outcomes of interest in this study, we assessed such reporting as linked to *probably low risk of bias*.
Conflict of interest	Probably low risk	Acknowledged support from an NGO.
Migration or survival bias	Probably low risk	Large study area covered, but data collected towards the end of the drought event, suggesting *probably low risk* of migration and survival bias.
Other bias	Low risk	No other potential biases suspected.

[1] Sample was representative of the drought affected population of Ethiopia, except pastoralist and semi-pastoralist populations in the Eastern periphery of the country.

Table 9—11. Risk of bias assessment summary for Gitau *et al*, 2005 [86].

Sources of bias	Rating	Support for the judgement
Exposure assessment	Probably high risk	Exposure was verified using indirect proxy indicator data: maize price data for the geographical area specific to the study population. However, maize prices could be affected by other factors than drought, and hence, not permit discerning between the effect of drought and the other factors.
Outcome assessment	Probably low risk	Although weight Z-scores were used, as opposed to the more traditional measure of weight-for-height or weight-for-age Z-scores, these were used consistently across the exposure groups, which was unlikely to bias estimates of the effect.
Sampling and recruitment strategy	Low risk	Sampling and recruitment strategy was consistent across exposure groups.
Blinding	Probably high risk	No blinding measures mentioned, unlikely that any were taken, which could have introduced bias.
Confounding	Probably high risk	Controlled for maternal Human Immunodeficiency Virus (HIV) status,[1] season, and other baseline differences between subjects (e.g., sex, age of mother at birth, proxies of mother's education and socio-economic status). Control for gestational age at birth did not have an effect and was excluded from the main results. However, there could have been other characteristics that changed over time and could have introduced confounding (e.g., concurrent events having similar effect to the effect of drought).
Incomplete outcome data	Probably high risk	Some loss to the follow up due to the participants' death, with a clustering of infant deaths around the time of the maize price increase. There is some evidence that the loss to follow up could be related to the outcome, which could have introduced bias.
Selective reporting	Low risk	All pre-specified outcomes reported in a pre-specified way.
Conflict of interest	Low risk	Study conducted by academics with financial support from the Wellcome Trust.
Migration or survival bias	Probably high risk	Probable survival bias, as infant deaths could have been related to higher food insecurity levels in their families. No measures were described as undertaken to prevent migration or survival bias.
Other bias	Low risk	No other potential biases suspected.

[1] Sample was based on infants born to middle-class women in hospital facilities stratified by mother's HIV status.

Table 9—12. Risk of bias assessment summary for Katona-Apte & Mokdad, 1998 [87].

Sources of bias	Rating	Support for the judgement
Exposure assessment	Probably low risk	Drought exposure was supported with data showing decreased agricultural production at the country level. Although data were not specified for the provinces examined in the study, the study covered 4 out of 9 provinces in North Korea, i.e., subjects were located across about half of the country. Therefore, we judged the risk of bias associated with the drought exposure assessment as *probably low*.
Outcome assessment	Probably high risk	Appropriate nutritional outcome measures used, however, anthropometric indices were assessed against the NCHS international growth reference which does not represent ideal growth that is possible in young children [4,5], and therefore, could have led to bias in the prevalence estimates of child undernutrition.
Sampling and recruitment strategy	High risk	Not necessarily a representative sample, participants could only be selected from the government permitted areas.
Blinding	Probably high risk	No blinding measures mentioned, but unlikely that any were taken, which could have introduced bias.
Confounding	Not applicable	The study was based on a single cross-sectional survey, providing data on nutritional outcome level during the drought.
Incomplete outcome data	Probably low risk	Some incomplete data, explained by exclusion of extreme values, proportion of excluded data was very low, compared to the sample size.
Selective reporting	Low risk	All pre-specified outcomes reported in a pre-specified way.
Conflict of interest	Probably high risk	Authors affiliated with an international organisation, with substantial involvement by the North Korean Government (all study protocols were approved by the North Korean Ministry of Foreign Affairs), authors suggested possible bias related to the influence of the government in the study design.
Migration or survival bias	Probably low risk	Severe drought and data collected in the first year of the drought, suggesting *probably low* risk of migration or survival bias.
Other bias	Low risk	No other potential biases suspected.

Table 9—13. Risk of bias assessment summary for Kumar & Bhavani, 2005 [88].

Sources of bias	Rating	Support for the judgement
Exposure assessment	Unclear	Drought exposure stated by the authors with no justification.
Outcome assessment	Probably high risk	Appropriate outcome measures of nutritional outcome used, however, anthropometric indices were assessed against the NCHS international growth reference, which does not represent ideal growth that is possible in young children [5,6], and therefore, could have led to bias in the prevalence estimates of child undernutrition.
Sampling and recruitment strategy	Probably low risk	Representative sample of the drought-affected population selected. Recruitment strategy not reported.
Blinding	Probably high risk	No blinding measures mentioned, unlikely that any were taken, which could have introduced bias.
Confounding	Not applicable	From the two surveys performed in this study, we considered only the first survey, i.e., initial drought-time survey as pertinent to the objective of our review. The second survey was undertaken only in the intervention villages to examine effectiveness of an intervention. Hence, we reviewed nutritional outcome results in relation to drought impact in this study based on a single cross-sectional survey undertaken during the drought.
Incomplete outcome data	Low risk	No incomplete outcome data.
Selective reporting	Low risk	All pre-specified outcomes reported in a pre-specified way.
Conflict of interest	Probably low risk	Author's affiliation with an international organisation was acknowledged.
Migration or survival bias	Probably high risk	Study conducted in a localized area with data collection towards the end of the drought, suggesting possible migration or survival bias. No measures were described as undertaken to prevent migration or survival bias.
Other bias	Low risk	No other potential biases suspected.

Table 9—14. Risk of bias assessment summary for Kumar *et al*, 2016 [89].

Sources of bias	Rating	Support for the judgement
Exposure assessment	Low risk	Drought exposure justified with monthly rainfall data specific for the study area.
Outcome assessment	Low risk	Appropriate nutritional outcome measures used, anthropometric indices assessed against the WHO child growth standards.
Sampling and recruitment strategy	Probably low risk	Representative sample of the population selected. Recruitment strategy not reported.
Blinding	Probably high risk	No blinding measures mentioned, unlikely that any were taken, which could have introduced bias.
Confounding	Probably low risk	Controlled for important potential confounders: year of birth, season of birth, linear birth-year trend specific to the season of birth, child age, sex, birth order, age of the mother at birth, indicators for parental education (whether mother and/or father are literate), whether the household belongs to a socially disadvantaged scheduled caste or scheduled tribe community, household religion, year and month of interview. Analyses were performed on drought exposure defined for each province individually, thus, reducing the risk of confounding by concurrent events that could have been influential for child undernutrition.
Incomplete outcome data	Probably low risk	Small fraction (4%) of incomplete data present but it was unlikely to have influenced results.
Selective reporting	Low risk	All pre-specified outcomes reported in a pre-specified way.
Conflict of interest	Low risk	No evidence of involvement of any other parties than academics.
Migration or survival bias	Low risk	Tests for the influence of selective migration and fertility demonstrated that such bias was unlikely.
Other bias	Low risk	No other potential biases suspected.

Table 9—15. Risk of bias assessment summary for Lindtjørn *et al*, 1990 [90].

Sources of bias	Rating	Support for the judgement
Exposure assessment	Unclear	Drought exposure was stated by the authors without any justification.
Outcome assessment	Probably low risk	Appropriate nutritional outcome measures used. Anthropometric indices assessed against the NCHS international growth reference across the comparison groups, which was unlikely to bias estimates of the effect.
Sampling and recruitment strategy	Unclear	Insufficient information on sampling and recruitment procedures.
Blinding	Probably high risk	No blinding measures mentioned, unlikely that any were taken, which could have introduced bias.
Confounding	High risk	No control for confounding.
Incomplete outcome data	Unclear	The reported information was not sufficient to determine completeness of the outcome data.
Selective reporting	Low risk	All pre-specified outcomes were reported in a pre-specified way.
Conflict of interest	Low risk	No evidence of involvement of other parties than academics.
Migration or survival bias	Probably high risk	Severe event in a localized area with data collected towards the end of the drought, which suggests that the study results could have been subjected to survival or migration bias. No measures were described as undertaken to prevent migration or survival bias.
Other bias	Low risk	No other potential biases suspected.

Table 9—16. Risk of bias assessment summary for Mahapatra *et al*, 2000 [91].

Sources of bias	Rating	Support for the judgement
Exposure assessment	Unclear	Drought exposure stated by the authors without any justification.
Outcome assessment	Probably high risk	Appropriate nutritional outcome measures used, anthropometric indices were assessed against the NCHS international growth reference, which does not represent ideal growth that is possible in young children [4,5], and therefore, could have led to bias in the prevalence estimates of child undernutrition. Micronutrient deficiencies were determined by observing their clinical signs. This method has been suggested to underestimate the prevalence of micronutrient deficiency [77,78].
Sampling and recruitment strategy	Probably low risk	Representative random samples obtained, but lack of explanation on how the 10% non-response rate was addressed.
Blinding	Probably high risk	No blinding measures mentioned, but unlikely that any were taken, which could have introduced bias.
Confounding	Not applicable	The study was based on a single cross-sectional survey, providing data on nutritional outcome levels during the drought.
Incomplete outcome data	Low risk	No incomplete outcome data.
Selective reporting	Low risk	All pre-specified outcomes reported in a pre-specified way.
Conflict of interest	Low risk	No evidence of involvement by other parties than academics.
Migration or survival bias	Probably low risk	Study conducted in a localized area, data collected in the first year of the drought, suggesting probably low risk of migration or survival bias.
Other bias	Low risk	No other potential biases suspected.

Table 9—17. Risk of bias assessment summary for Mason *et al*, 2005 [92].

Sources of bias	Rating	Support for the judgement
Exposure assessment	Low risk	Drought exposure stated by the authors and justified with a reference that provides data on a food crisis, explaining that the food crisis was in part attributed to drought conditions.
Outcome assessment	Probably low risk	Appropriate nutritional outcome measures used. The NCHS international growth reference was used for the assessment of anthropometric indices consistently across the comparison groups, which was unlikely to bias the estimates of effect.
Sampling and recruitment strategy	Probably low risk	Representative random samples obtained. Lack of information on the recruitment strategy, but likely to have been consistent.
Blinding	Probably high risk	No blinding measures mentioned, unlikely that any were taken, which could have introduced bias.
Confounding	Probably high risk	Although survey comparability was ensured, authors acknowledged that their results could be subject to ecological fallacy.
Incomplete outcome data	Unclear	The reported information was not sufficient to determine completeness of the outcome data.
Selective reporting	Low risk	All pre-specified outcomes reported in a pre-specified way.
Conflict of interest	Probably low risk	Acknowledged author's affiliation with an international organisation.
Migration or survival bias	Low risk	Study conducted in a large geographical area examining a short period of drought examining outcomes measured in the same year, and hence, suggesting low risk of migration or survival bias.
Other bias	Low risk	No other potential biases suspected.

Table 9—18. Risk of bias assessment summary for Mason *et al*, 2010 [93].

Sources of bias	Rating	Support for the judgement
Exposure assessment	Low risk	Drought exposure was described and justified using an index based on agricultural production data, which we judged as sufficient for the classification of drought conditions.
Outcome assessment	Probably low risk	Appropriate nutritional outcome measures used. The NCHS international growth reference was used in the assessment of anthropometric indices consistently across the comparison groups, which was unlikely to bias estimates of the effect.
Sampling and recruitment strategy	Probably low risk	Representative random samples obtained. Lack of information on the recruitment strategy, but likely to have been consistent.
Blinding	Probably high risk	No blinding measures mentioned, unlikely that any were taken, which could have introduced bias.
Confounding	High risk	No control for confounding, likelihood of ecological fallacy.
Incomplete outcome data	Unclear	The reported information was not sufficient to determine completeness of the outcome data.
Selective reporting	Low risk	All pre-specified outcomes reported in a pre-specified way.
Conflict of interest	Probably low risk	Acknowledged author's affiliation with an international organisation.
Migration or survival bias	Low risk	Study conducted in a large geographical area, examining short periods of drought and relating drought indicator values to the outcomes measured in the same year, and suggesting low risk of migration or survival bias.
Other bias	Low risk	No other potential biases suspected.

Table 9—19. Risk of bias assessment summary for Mason *et al*, 2010 [94].

Sources of bias	Rating	Support for the judgement
Exposure assessment	Low risk	Drought exposure was described and justified using an index based on data from the Food and Agriculture Organization (FAO) food security reports, which we judged as sufficient for the classification of drought conditions.
Outcome assessment	Probably low risk	Appropriate nutritional outcome measures used. The NCHS international growth reference was used for the assessment of anthropometric indices consistently across the comparison groups, which was unlikely to bias estimates of the effect.
Sampling and recruitment strategy	Probably low risk	Representative random samples obtained. Lack of information on the recruitment strategy, but likely to have been consistent.
Blinding	Probably high risk	No blinding measures mentioned, unlikely that any were taken, which could have introduced bias.
Confounding	High risk	No control for confounding, likelihood of ecological fallacy.
Incomplete outcome data	Unclear	The reported information was not sufficient to determine completeness of the outcome data.
Selective reporting	Low risk	All pre-specified outcomes reported in a pre-specified way.
Conflict of interest	Probably low risk	Acknowledged author's affiliation with an international organisation and NGO.
Migration or survival bias	Low risk	Study conducted in a large geographical area, examining short periods of drought, and relating drought indicator values to outcomes measured in the same year, suggesting low risk of migration or survival bias.
Other bias	Low risk	No other potential biases suspected.

Table 9—20. Risk of bias assessment summary for McDonald *et al*, 1994 [95].

Sources of bias	Rating	Support for the judgement
Exposure assessment	Probably high risk	Relevant drought exposure data was presented at the country level and was not necessarily specific for the study area, which could have introduced some bias.
Outcome assessment	Probably low risk	Appropriate nutritional outcome measures used. The NCHS international growth reference was used for the assessment of anthropometric indices consistently across the comparison groups, which was unlikely to bias the estimates of effect.
Sampling and recruitment strategy	Probably high risk	Possibly purposeful sampling strategy used, details of the sampling and recruitment strategy were unclear.
Blinding	Probably high risk	No blinding measures mentioned, unlikely that any were taken, which could have introduced bias.
Confounding	Probably high risk	Study design accounted for important potential confounding at the individual level. Yet, it was not controlled for possible confounding by concurrent events that may influence child nutritional status.
Incomplete outcome data	Probably high risk	Incomplete data was present. No reason or explanation was provided for the incomplete data. The same subjects appear to have been missing from analyses throughout all study time. The incomplete data could have possibly introduced bias in the estimates of the effect.
Selective reporting	Low risk	All pre-specified outcomes reported in a pre-specified way.
Conflict of interest	Probably low risk	Acknowledged author's affiliation with an international organisation and NGO.
Migration or survival bias	Probably high risk	Information on why data on 12 toddlers was not included in the analysis was not provided. This exclusion could have been related to migration/survival; no measures were described as taken to address such bias.
Other bias	Low risk	No other potential biases suspected.

Table 9—21. Risk of bias assessment summary for Moloney *et al*, 2011 [96].

Sources of bias	Rating	Support for the judgement
Exposure assessment	Unclear	Drought exposure stated by the authors with no justification.
Outcome assessment	Low risk	Appropriate nutritional outcome measures used. The WHO child growth standards were used to assess anthropometric indices.
Sampling and recruitment strategy	Probably low risk	Representative random samples obtained. Lack of information on the recruitment strategy. Some indication that sampling and recruitment strategies were consistent across the comparison groups was provided by the statement that the surveys, whose data was used in the study, were based on standard methodology (Lot Quality Assurance sampling method and SMART method).
Blinding	Probably high risk	No blinding measures mentioned, unlikely that any were taken, which could have introduced bias.
Confounding	Not applicable	The study was based on a single cross-sectional survey, providing data on nutritional outcome level during the drought.
Incomplete outcome data	Unclear	The reported information was not sufficient to determine completeness of the outcome data.
Selective reporting	Probably low risk	Format of the article did not allow pre-specifying the outcomes in the abstract and introduction. The outcomes that were pre-specified in the methods section and were reported in the results.
Conflict of interest	Probably low risk	Some authors affiliated to a government agency.
Migration or survival bias	Probably high risk	Severe event, examined in geographically localized areas, data collected 1.5 years since the start of the drought, suggesting possible migration or survival bias. No measures were described as undertaken to prevent migration or survival bias.
Other bias	Low risk	No other potential biases suspected.

Table 9—22. Risk of bias assessment summary for Mude & Barrett, 2008 [97].

Sources of bias	Rating	Support for the judgement
Exposure assessment	Low risk	Drought exposure justified by rainfall and forage data.
Outcome assessment	Probably low risk	Appropriate nutritional outcome measures used. The NCHS international growth reference was used for the assessment of anthropometric indices consistently across all comparison groups, which was unlikely to bias estimates of the effect.
Sampling and recruitment strategy	Unclear	Specifics of the sampling strategy were not known to the authors, poor data management practices acknowledged, lack of information on recruitment strategy.
Blinding	Probably high risk	No blinding measures mentioned, unlikely that any were taken, which could have introduced bias.
Confounding	High risk	No control for confounding, as only correlation of the exposure and outcome measures was examined.
Incomplete outcome data	Probably high risk	Only a fraction of the data was used for analysis due to poor data management practices.
Selective reporting	Low risk	All pre-specified outcomes reported in a pre-specified way.
Conflict of interest	Probably low risk	Funding received from a specialized government agency.
Migration or survival bias	Probably low risk	Study conducted in a localized area with data collection starting from the first year of the drought, which suggests probably low risk of migration or survival bias.
Other bias	Low risk	No other potential biases suspected.

Table 9—23. Risk of bias assessment summary for Renzaho *et al*, 2006 [98].

Sources of bias	Rating	Support for the judgement
Exposure assessment	Probably low risk	Drought exposure justified with some years of data on agricultural production, but the time period for which data was provided was too short to fully illustrate drought event relatively to the production levels before and after the event. Hence, the data did not provide a sufficient level of confidence for the judgement *low risk of bias* but nevertheless provided indirect evidence for the judgement *probably low risk of bias*.
Outcome assessment	Unclear	Lack of information on how anthropometric indices of the outcome measures were calculated.
Sampling and recruitment strategy	Low risk	Representative population sample was obtained. Appropriate recruitment strategy used, addressing cases of non-response in a consistent and adequate manner.
Blinding	Probably high risk	No blinding measures mentioned, unlikely that any were taken, which could have introduced bias.
Confounding	Not applicable	A single cross-sectional survey, providing data on nutritional outcome level after the drought.
Incomplete outcome data	Low risk	No incomplete outcome data.
Selective reporting	Low risk	All pre-specified outcomes reported in a pre-specified way.
Conflict of interest	Probably low risk	Study funded and conducted by an NGO.
Migration or survival bias	Probably high risk	Study conducted in a localized area after a drought, which suggests that the study results could have been subjected to migration or/and survival bias. No measures were described as undertaken to prevent migration or survival bias.
Other bias	Low risk	No other potential biases suspected.

Table 9—24. Risk of bias assessment summary for Renzaho *et al*, 2006 [99].

Sources of bias	Rating	Support for the judgement
Exposure assessment	Low risk	Drought exposure justified with references to food insecurity estimates and water shortages, which were related to drought conditions.
Outcome assessment	Unclear	Lack of information on how anthropometric indices (outcome measures) were calculated.
Sampling and recruitment strategy	Low risk	Representative population sample was obtained. Appropriate recruitment strategy used, addressing cases of non-response in a consistent and adequate manner.
Blinding	Probably high risk	No blinding measures mentioned, unlikely that any were taken, which could have introduced bias.
Confounding	Not applicable	The study was based on a single cross-sectional survey, providing data on nutritional outcome levels after the drought.
Incomplete outcome data	Low risk	No incomplete outcome data.
Selective reporting	Low risk	All pre-specified outcomes reported in a pre-specified way.
Conflict of interest	Probably low risk	Study funded and conducted by an NGO.
Migration or survival bias	Probably high risk	Study conducted in a localized area after a drought, which suggests that the study results could have been subjected to survival or migration bias. No measures were described as undertaken to prevent migration or survival bias.
Other bias	Low risk	No other potential biases suspected.

Table 9—25. Risk of bias assessment summary for Singh *et al*, 2006 [100].

Sources of bias	**Rating**	**Support for the judgement**
Exposure assessment	Unclear	Drought exposure stated by the authors with no justification.
Outcome assessment	Probably high risk	Appropriate nutritional outcome measures used. Anthropometric indices were assessed against the NCHS international growth reference which does not represent ideal growth that is possible in young children [4,5], and therefore, could have led to bias in the prevalence estimates of child undernutrition. Micronutrient deficiencies were determined by observing their clinical signs. This method has been suggested to underestimate the prevalence of micronutrient deficiency [77,78].
Sampling and recruitment strategy	Probably low risk	Representative sample of the population selected. Recruitment strategy not reported.
Blinding	Probably high risk	No blinding measures mentioned, unlikely that any were taken, which could have introduced bias.
Confounding	Not applicable	A single cross-sectional survey, providing data on nutritional outcome levels during the drought.
Incomplete outcome data	Probably low risk	Some incomplete data present (1%), yet due to its small proportion, it was unlikely to have introduced bias.
Selective reporting	Low risk	All pre-specified outcomes reported in a pre-specified way.
Conflict of interest	Low risk	Study conducted by academics with no evidence of involvement by other parties.
Migration or survival bias	Probably high risk	Study conducted in a localized area, which was one of the worst drought affected areas of the country, suggesting possible migration or survival bias.
Other bias	Low risk	No other potential biases suspected.

Table 9—26. Risk of bias assessment summary for Venkaiah *et al*, 2015 [101].

Sources of bias	Rating	Support for the judgement
Exposure assessment	Probably low risk	Drought exposure justified by referring to a government declaration of drought in areas specific to the study population. The declaration could be based on the assessment of appropriate indicators. However, article did not provide any reference to such assessment.
Outcome assessment	Probably high risk	Appropriate outcome measures of nutritional outcome used. However, anthropometric indices were assessed against the NCHS international growth reference which does not represent ideal growth that is possible in young children [4,5], and therefore, could have led to bias in the prevalence estimates of child undernutrition. Micronutrient deficiencies were determined by observing their clinical signs. This method has been suggested to underestimate the prevalence of micronutrient deficiency [77,78].
Sampling and recruitment strategy	Probably low risk	Representative sample of the population selected. Recruitment strategy not reported.
Blinding	Probably high risk	No blinding measures mentioned, unlikely that any were taken, which could have introduced bias.
Confounding	Not applicable	The study was based on a single cross-sectional survey, providing data on nutritional outcome levels during the drought.
Incomplete outcome data	Unclear	The reported information was not sufficient to determine completeness of the outcome data.
Selective reporting	High risk	Clinical nutritional deficiency examination was stated in the study aim but there were no results presented. Results of morbidity data were reported without any pre-specification.
Conflict of interest	Probably low risk	Involvement of staff from a government agency was acknowledged.
Migration or survival bias	Probably low risk	Data collected in the beginning of the drought in several Indian states, which suggests probably low risk of migration or survival bias.
Other bias	Low risk	No other potential biases suspected.

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Annex 4: Supplementary material for Paper 4 *The mortality burden of low crop yields in the context of current and future climates*

1. Further detail on the statistical crop model

The crop model was based on a time-series analysis originally developed by Gornott and Wechsung,[1] which here we calibrated using crop yield data for Kossi province of Burkina Faso. Adjustments to the model and considerations additional to those provided in Gornott and Wechsung[1] are detailed below.

1) Adjustments to model development

(1) We assumed the following crop growing seasons for our study area: for maize and millet 1 August–31 October, rice 1 May–31 October, sorghum 15 March–31 October, and fonio 15 April–15 September. These were consistent with information from the local agricultural authority, agricultural crop calendar of the Food and Agriculture Organisation (FAO), and the Global Yield Gap and Water Productivity Atlas (Yield Gap).[2,3]

(2) Variables for each crop type model were selected on the basis of plant physiology and following the conceptual framework of Gornott & Wechsung[1] and Schauberger *et al*[4] The weather variables were calculated using WFDEI (Water and Global Change Forcing Data Methodology Applied to the European Centre for Medium-Range Weather Forecasts Interim Re-Analysis) data[5] for the crop growth season, as specified in Table 9–27.

Table 9—27. Weather variables used for the construction of the crop-specific statistical models.

Variable	Unit	Purpose	Calculation
solar radiation (SR)	J/cm²	to determine crop growth potential	sum over the growing season
precipitation (*PREC*)	mm	to capture deviations from the optimal plant water supply	sum over the growing season
vapour pressure deficit (*VPD*)	mm	to capture the atmospheric water demand	sum of daily vapour pressure deficit values over the growing season, as derived from the maximum ($TMP_{\max}$) and minimum temperature ($TMP_{\min}$)[6,7] $VPD = 6 \cdot 11 \left(e^{\left(\frac{17.269\, TMP_{\max}}{237.3 + TMP_{\max}}\right)} - e^{\left(\frac{17.269\, TMP_{\min}}{237.3 + TMP_{\min}}\right)} \right)$
growing degree days (*GDD*)	°C	to explain the (positive) influence on crop growth	sum of days with daily mean temperature falling within the range of optimal temperature for the growing season, 30–8 °C for all examined crops
killing degree days (*KDD*)	°C	to account for temperatures leading to heat stress and potentially negative impact on crop yields[8]	cumulated temperature sum of daily mean temperature above the optimal temperature (of 30 °C) over the growing season
days without precipitation (*DWP*)	days	to capture precipitation distribution which might hamper the crop development	sum of days with no precipitation over the growing season, identified as follows: $DWP_t = \sum_{d=1}^{D} dwp_d = \begin{cases} 1, & \text{if } PREC_d = 0 \\ 0, & \text{if } PREC_d > 0 \end{cases}$ d = the day within each of the crop development periods ($d = 1, \dots, D$)
dry spells longer than 5 days (*SP5*)	days	to capture crop yield impact of the dry spells	number of days with dry spells longer than 5 days over the growing season, identified as: $SP5_t = \sum_{d=1}^{D} SP5_d = \left\{ \begin{matrix} 1 & \text{if } RD_d \geq 5 \;\&\; RD_{d+1} = 0 \\ 0 & \text{if } RD_d \geq 5 \;\&\; RD_{d+1} \neq 0 \end{matrix} \right\}$ with $RD_d = \left\{ \begin{matrix} RD_{d-1} + 1 & \text{if } PREC_d < 0.5 \\ 0 & \text{if } PREC_d \geq 0.5 \end{matrix} \right\}$ and RD as rainy day;
heavy precipitation events >40mm per day (*PE40*)	number of the events	to capture negative impact of soil erosion and nitrogen leaching	number of events over the growing season, identified as: $PE_t = \sum_{d=1}^{D} PE_d = \left\{ \begin{matrix} 1 & \text{if } PREC_d \geq 20 \\ 0 & \text{if } PREC_d < 20 \end{matrix} \right\}$
acreage	ha	to capture changes in agronomic management practices and land use[9] in the model	hectares of land cultivated under the respective crop type in Kossi province

2) Additional aspects of model application

(1) Our model is estimated with log-transformed functional form (Cobb–Douglas production function).[10,11] We applied fixed effects transformation to the endogenous variable crop yield and the vector of G exogenous weather, H exogenous economic variables (here only acreage), and I exogenous dummy variables – used to control for extreme yield anomalies, as in Albers et al.[12,13]

[eq1]

$$\log \ddot{y}_{jt} = \sum_{g=1}^{G} \beta_{jg} \log\, \ddot{x}_{jgt} + \sum_{h=1}^{H} \beta_{jh} \log\, \ddot{x}_{jht} + \sum_{i=1}^{I} \beta_{ji}\, x_{jit} + \log \ddot{u}_{jt}$$

$\log \ddot{y}_t = \log\left(\frac{y_t}{\bar{y}}\right)$, *$\bar{y}$ as arithmetic average of y_t and respectively for x and u. The term β represents the parameters, u is the error term, and t as the time-index (with t=1,…,T).*

The weather-related yields are calculated by the retransformation of the model equation. The variable acreage was set constant to estimate only the part of yield variability that is attributable to weather.

[eq2]

$$y_{jt} = \exp\left(\left(\sum_{g=1}^{G} \beta_{jg} \log\, \ddot{x}_{jgt} + \sum_{h=1}^{H} \beta_{jh}\, \overline{\log \ddot{x}_{jht}} + \sum_{i=1}^{I} \beta_{ji}\, x_{jit}\right) + \overline{\log y_{jt}}\right)$$

(2) To project crop yield variation under the global warming of 1·5 °C, we applied the regression coefficients from the crop models to climate data derived from two General Circulation Model (GCM) realizations provided by the Inter-Sectoral Impact Model Inter-comparison Project (ISI-MIP2b): IPSL-CM5A-LR (Institute Pierre Simon Laplace Climate Model) and MIROC5 (Model for Interdisciplinary Research on Climate).[14] We did not use the third model GFDL-ESM2M (Geophysical Fluid Dynamics Laboratory – Earth System Models including Modular Ocean Model version 4.1), as it was unable to sufficiently reproduce the observed weather conditions. The GCM realizations were corrected against reanalysed weather observations by the ISI-MIP. We used a similar calculation to the calculation of the weather attributable yields when projecting the weather impacts on the crop-specific yields (*β_{jg}*) to the new time period t^*(2000–2100) [eq2].

3) Model assumptions

The crop models were based on the following assumptions:

(1) We assumed the relationship of weather and management impacts on crop yields to be linear

Since we use a statistical regression model with only linear exogenous variables, non-linear yield impacts were not considered, which corresponds to the approach of Schlenker & Roberts.[16] To ensure that our models did not omit such impacts, we conducted a statistical test (RESET).[17]

(2) We assumed that weather variables have equal impact on yield at every stage of crop development

The magnitude of the effect of weather variation on crop yield, in terms of grain quantity and quality, differs depending on the stage of crop development during which the crop was exposed to these weather variations.[18] However, many statistical crop models, e.g., the models of Moore & Lobell,[19] Blanc,[13] and You *et al*,[11] did not divide the growing period into sub-periods to allow for differential impact of weather variables in these sub-periods and showed that weather variables aggregated over the entire growing season are able to sufficiently explain crop yield variability. We used the out of sample cross validation to corroborate the robustness of our crop models (in which weather variables were aggregated over the entire growing season) for yield estimation beyond the time period of the observed yield data. The out of sample cross validation confirmed the robustness of our models.

(3) We assumed that estimated model parameters are valid for the future climate conditions of 1·5 °C warming

Estes *et al*[20] and Lobell & Burke[21] show that statistical models have a high capacity to reproduce observed conditions (often better than process-based models), however, they are more limited in their ability to project unobserved conditions. As the future climate conditions under 1·5 °C of global warming may be relatively similar to the current climate conditions, we assumed that our model parameters are valid for these conditions. A comparison of the past and future climate data showed that the range of the inter-annual weather variability observed in the past included most of the variability projected under the 1·5 °C of global warming.

(4) We assumed that fixed effects transformation controls for any time-invariant effects, such as soil conditions, market access, and land tenure, which we assumed to be time-invariant

Our model captures time-invariant effects like the soil conditions or other farm-specific conditions though the fixed effects variable transformation.[22] The fixed effect transformation eliminates time-invariant effects in the data by capturing them implicitly in the statistical model. We assumed that the transformation allows for the control of such factors as investment in agricultural equipment, market access, land tenure security, and soil conditions.[23,24] Under these assumptions, we suggest that the model parameters are not biased by these time-invariant effects (no omitted variable bias).

(5) Management impacts are reflected by crop acreage

Often, information on agronomic management is not available for many regions in sub-Saharan Africa.[25] Since changes in acreage are often an indicator of changes in soil quality and available labour, we used acreage to capture possible effects of such factors.[9,26]

4. Additional considerations in model validation

(1) The model goodness of fit and the out of sample cross validation of the statistical models:[1] $R^2 = 0{\cdot}64$ ($R^2 = 0{\cdot}21$) for millet, $R^2 = 0{\cdot}55$ ($R^2 = 0{\cdot}02$) for sorghum, $R^2 = 0{\cdot}51$ ($R^2 = 0{\cdot}26$) for maize, $R^2 = 0{\cdot}92$ ($R^2 = 0{\cdot}58$) for fonio, and $R^2 = 0{\cdot}53$ ($R^2 = 0{\cdot}16$) for rice.

(2) The weather variables largely explained the observed crop yield variability. In comparison to the full model (in parenthesis), the weather variables explained the following percentage of yield variability: 50% (51%) for maize, 86% (92%) for fonio, 63% (64%) for millet, 51% (53%) for rice, and 54% (55%) for sorghum. Although the effect of the acreage is rather small, it was retained in the model as a measure of reducing the risk of bias. In Kossi, acreage of the respective crops shows strong inter-annual changes and there has been a long-term increase in fonio and millet by 64% (10-year averages) and 36% respectively. The maize and sorghum acreage declined by 57% and 45%. Rice acreage shows a very strong increase of +337%, but this is mostly driven by a few observations in the mid-1990s and from 2008 to 2010 much above the average level. Yet, mostly the variable acreage shows

no significant contribution to the explained yield variability. Despite this strong inter-annual and long-term change, we concluded that land productivity was unlikely to have changed in this period and that the farmers have not moved to less suitable land.

(3) We conducted several statistical tests to verify model robustness and validity. The statistical tests are described by Croissant & Millo.[17] The regression equation specification error test (RESET) was used to investigate whether quadratic variables are missed in the model. The RESET showed that quadratic variables were not neglected for any of the crops. The Breusch–Godfrey and Breusch–Pagan tests were applied to test against autocorrelation and heteroscedasticity. In two cases the model residuals were autocorrelated (fonio and millet), the other crops show no autocorrelation (Breusch–Godfrey test). As the time series are relatively short (T=28) and the variable transformation tends to cause autocorrelation,[27] we judged that this was unlikely to bias parameters in the models of fonio and millet. There appeared to be no heteroscedasticity (Breusch–Pagan test) in any of the models. The distribution of residuals was tested using the Shapiro–Wilk test, suggesting normal distribution of residuals in all models.

2. Supplementary figures and tables

Table 9–28 provides uncertainty estimates of the results reported in Table 6–1 of the main text. Across columns and rows of the table, lower and upper bound estimates were based on different sources of uncertainty.

First and third columns (from the left): uncertainty estimates derived using the 95% confidence interval bounds (instead of the central estimate) of the risk ratio of child survival in relation to crop yield.

Second and fourth columns (from the left): uncertainty estimates derived using the 95% confidence interval bounds (instead of the central estimates) of the risk ratio of child survival in relation to crop yield[28] and of the estimates of the weather-attributed part of crop yield variation.

Additionally to the parameter of uncertainty, detailed above, uncertainty estimates of the monetized equivalent cost of YLL also account for the higher (1·4) and lower (1·0) assumptions of income elasticity.

Table 9—28. Central (and uncertainty) estimates of the mortality impact of crop deficits and weather-related crop deficits as well as their costs under the climate over the period of 1984–2012.

	Average year*		**Worst year (2000)**	
	Overall	**Weather-related**	**Overall**	**Weather-related**
Mortality impact per 100 thousand people of all ages				
Child <5y deaths	7	5	41	39
	(1, 44)	(0, 45)	(8, 225)	(2, 225)
YLL (not discounted)	438	331	2,634	2,529
	(84, 2,838)	(10, 2,918)	(529, 14,568)	(150, 14,536)
Costs (thousand 2011 USD, PPP-corrected) per 100 thousand people				
Cost of crop deficit	186	135	802	776
	(n/a)	(0, 205)	(n/a)	(0, 807)
Monetized equivalent cost of YLL**, discounted at				
6%	260	196	1,552	1,490
	(25, 3,433)	(3, 3,544)	(153, 17,479)	(43, 34,190)
3%	474	358	2,834	2,720
	(45, 6,264)	(5, 6,452)	(279, 31,928)	(79, 46,166)
0%	1,166	882	6,974	6,695
	(110, 15,331)	(13, 15,763)	(686, 78,597)	(195, 78,426)

*Deficits in years with FCPI<90% averaged across all years of the period 1984–2012.

**We used the period average VSLY of 2,663 USD for the central estimate (income elasticity of 1·2), 1,315 USD for the lower bound estimate (income elasticity of 1·4), and 5,402 USD for the upper bound estimate (income elasticity of 1·0). For the worst year (i.e., 2000) we used the VSLY of 2,647 USD for the central estimate (income elasticity of 1·2), 1,299 USD for the lower bound estimate (income elasticity of 1·4), and 5,395 USD for the upper bound estimate (income elasticity of 1·0).[21] All indicated in 2011 USD, PPP-corrected.

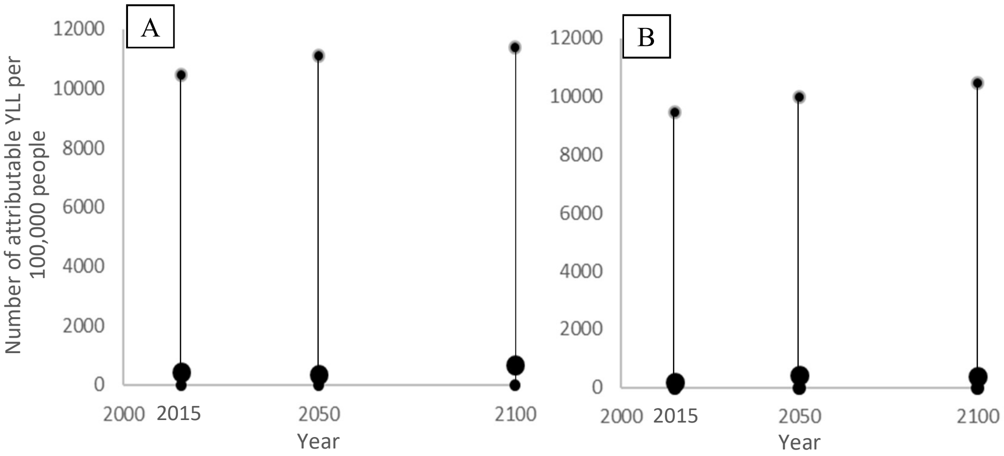

Figure 9—1. Central and uncertainty estimates of the annual average attributable years of life lost per 100 thousand people of all ages under 1·5 °C global warming for three 30-year periods centred on years 2015, 2050, and 2100.

The uncertainty estimate are based on the lower and upper bounds of the 95% confidence intervals of the model parameters, i.e., mortality risk ratio and crop yield projections.
A – based on weather projected using the IPSL-CM5A-LR GCM
B – based on weather projected using the MIROC5 GCM

Note: the lower estimates in the projections are equal to 0 as a result of our assumption that mortality impact is incurred only in years with yield <90% of the average over the period of 1992–2012. The lower bound of the modelled crop yield estimates in all cases exceeded 90% FCPI, hence, not incurring mortality impact as a result of our modelling assumption that mortality impact is only incurred in years with FCPI <90%.

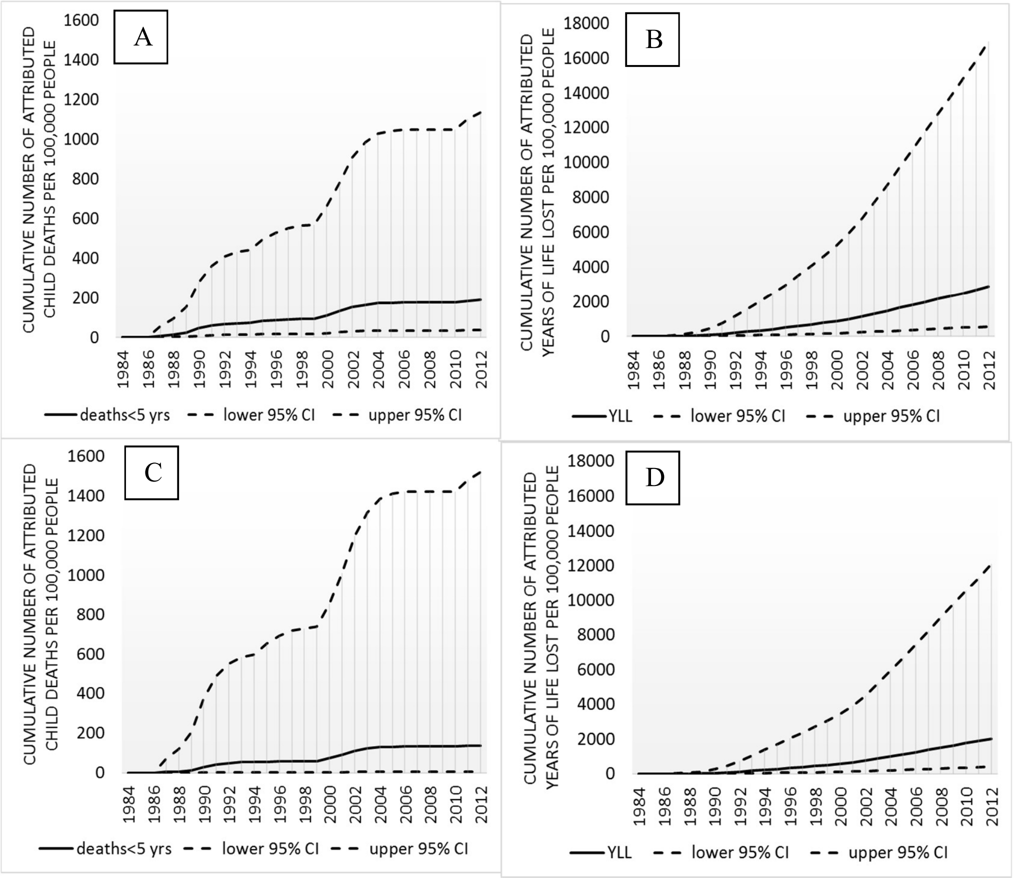

Figure 9—2. Cumulative mortality impact per 100 thousand people of all ages attributable to crop yield deficits in years with FCPI<90%: [A] child deaths <5 years, [B] YLL; corresponding numbers for weather-related crop deficits: [C] child deaths <5 years, [D] YLL.

Dashed lines represent uncertainty estimates based on 95% confidence intervals of the relative risk for child mortality used in the calculations.

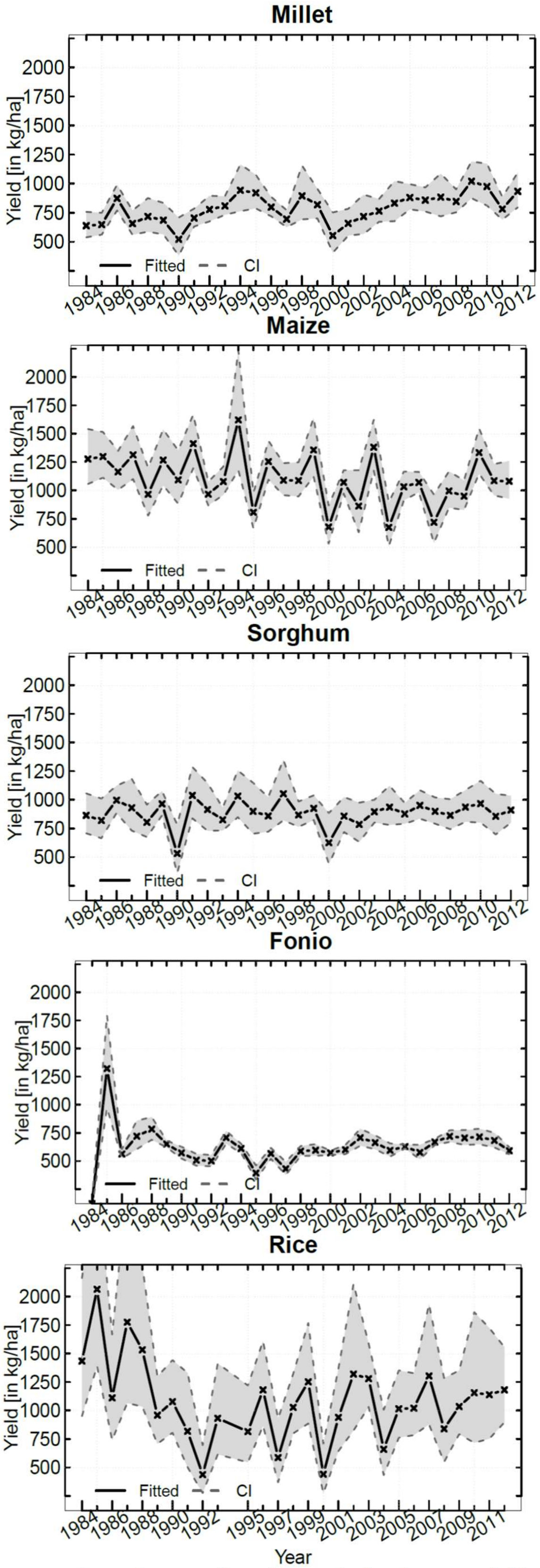

Figure 9—3. Estimates of weather-attributable variation in crop yields, Kossi province, Burkina Faso, 1984–2012, based on estimates of the statistical crop model. Shaded bands indicate 95% confidence intervals.

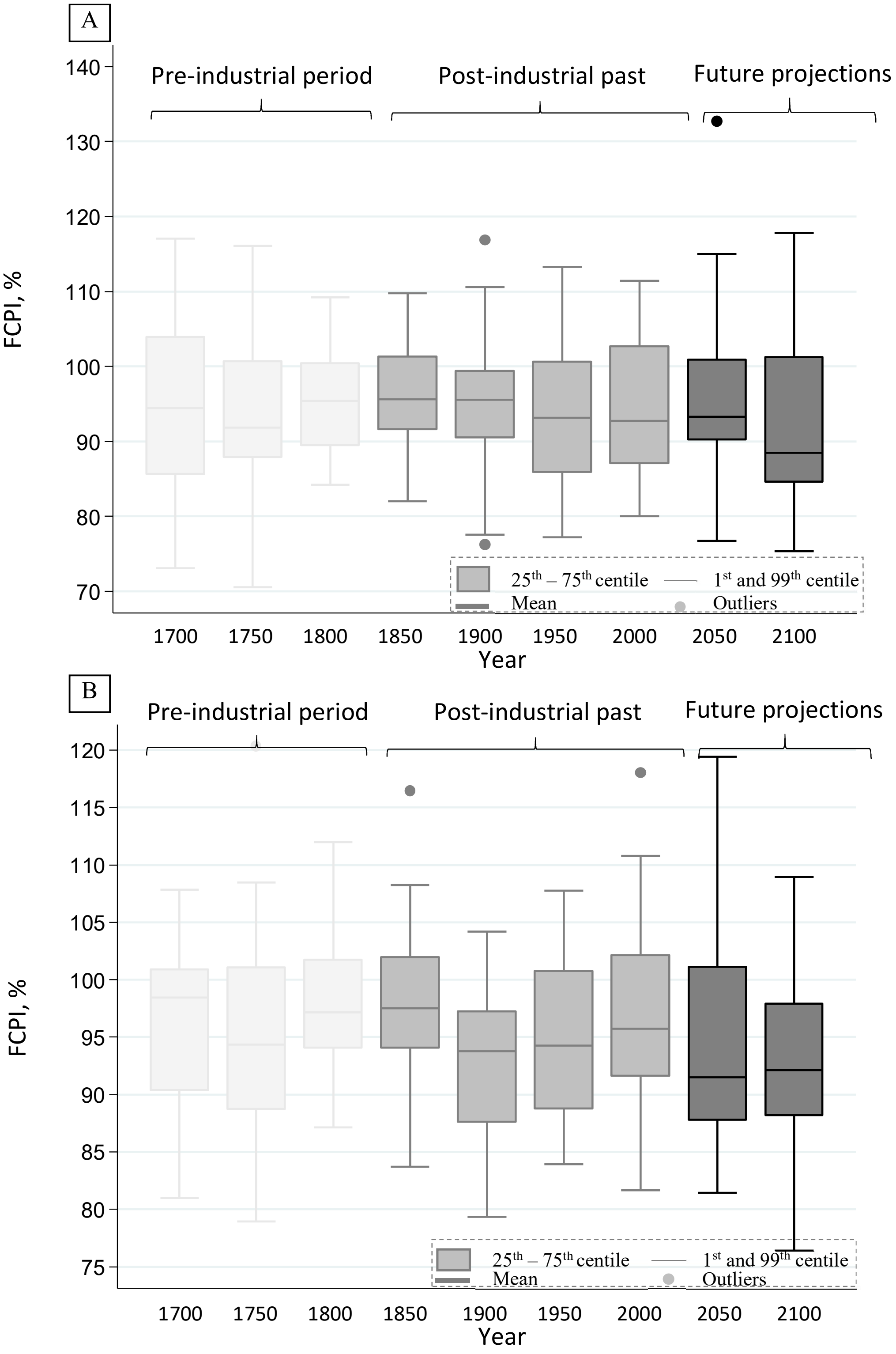

Figure 9—4. Food Crop Productivity Index (FCPI) projections based on climate data of each of the general circulation models separately: A – IPSL-CM5A-LR, B – MIROC5. Each box plot is based on data from a 30-year time period centred on the year indicated on the horizontal axis.

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