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ORIGINAL PAPER

Agricultural droughts and under-five mortality in Côte d'Ivoire: Differential impacts across social and demographic groups

Liliana Andriano[1]

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Abstract

Little research explores how climate extremes affect early childhood mortality in sub-Saharan Africa, despite great vulnerability to both climate extremes and high rates of early childhood mortality. Although there have been substantial improvements in early childhood mortality in recent decades, climate change threatens to offset this progress. Focusing on the case of Côte d'Ivoire, I combine individual-level data from the Demographic and Health Surveys with high-resolution climate data to investigate how and when in-utero exposure to severe agricultural droughts influences early childhood mortality. I find that in-utero exposure to severe agricultural droughts increases the probability of under-five mortality, and most recent droughts seem to exert the greatest impact. I also find that boys and children born into families with little to no formal education are highly vulnerable to drought exposure during gestation. Maternal education mitigates the negative impact of droughts on under-five survival, regardless of urban or rural residence, suggesting that its protective effects may be linked to specific knowledge, behaviours, and practices that highly educated mothers employ rather than their living environment. These findings carry important lessons for policymakers, emphasising the need for policies that enhance educational opportunities for parents and develop targeted interventions for boys and children from families with little formal education.

Keywords Climate extremes · Under-five mortality · Droughts · Africa

Introduction

Cote d'Ivoire's economy is heavily reliant on agriculture, with a large proportion of the population engaged in rainfed subsistence farming. Less than 1% of the cultivated land is equipped with irrigation facilities, making food security and general

✉ Liliana Andriano
L.Andriano@soton.ac.uk

[1] Department of Social Statistics and Demography, University of Southampton, Southampton SO17 1BJ, UK

livelihood highly dependent on climatic conditions (FAO et al., 2018; World Bank, 2021a). When the country experienced a series of severe droughts over the past decades (Côte d'Ivoire MINESUDD, 2014), the resulting crop losses undermined food security and negatively impacted the well-being of the people in Côte d'Ivoire (FAO et al., 2018). Projections show further increases in temperatures and dry spell length (AfDB, 2018; World Bank, 2021a; Yapo et al., 2020) which will place additional pressure on food security in a country where 27.3% of child deaths are associated with undernutrition (WFP, 2022).

In recent years, there have been substantial improvements in early childhood mortality in Côte d'Ivoire, with under-five deaths more than halving between 1990 and 2021, decreasing to 75 deaths per 1,000 live births in 2021 (UN IGME, 2023). However, extreme weather has the potential to offset this progress. This study investigates how and when in-utero exposure to agricultural droughts impacts under-five mortality and explores how this impact varies based on demographic and socioeconomic characteristics. The study sample consists of all under-five children from the Côte d'Ivoire Demographic and Health Surveys. The individual-level data, which include information on the child's date of birth and geographic location, are combined with local high-resolution spatial data on climate to create a measure of in-utero exposure to agricultural droughts as measured by the Standardised Precipitation Evapotranspiration Index (SPEI). This paper makes three main contributions to the demographic literature on the effect of in-utero exposure to weather events on early childhood mortality.

First, previous literature has primarily focused on the mortality consequences of in-utero drought exposure for infants (Flatø & Kotsadam, 2014; Kudamatsu et al., 2012; Kumar et al., 2016; Rocha & Soares, 2015), thus neglecting its effect on mortality among slightly older children (i.e. ages one through four). Given that childhood deaths in low-income countries occur at high rates between ages one and five (UN IGME, 2023), focusing solely on infant mortality may lead to an underestimation of the adverse effects of drought on early childhood mortality. I not only investigate the impact of in-utero exposure to droughts on under-five mortality but also comprehensively analyse the timing underpinning this impact.

The second contribution of this work is methodological and relates to the measure of drought. Previous research investigating the impact of in-utero exposure to drought on child health outcomes often defines droughts simply as a lack of rainfall. However, as we learn from the meteorological literature (Masih et al., 2014; WMO, 1975), droughts are not solely caused by decreased precipitation: increases in evaporation from soil and vegetation—mainly due to warmer temperatures—also contribute significantly (Vicente-Serrano et al., 2012). In this work, I adopt a more comprehensive measure of drought exposure that incorporates numerous climate parameters beyond just precipitation: the SPEI. Widely recognised as the most complete and robust agricultural drought index in Africa (WMO, 2012), the SPEI is employed here for the first time in combination with demographic data on early childhood mortality.

The third contribution of this work is to investigate the extent to which key demographic and socioeconomic factors can mitigate children's vulnerability to climate extremes in-utero. By examining how individual, household, and community-level factors—such as child's sex, parental level of education, household wealth, and place of residence—modify the degree of susceptibility to under-five mortality, this analysis pinpoints specific population subgroups that require targeted policy interventions (Andriano, 2023; Dimitrova, 2021; Dimitrova & Muttarak, 2020; Muttarak et al., 2015).

The effects of weather shocks on early childhood health and mortality: Existing evidence base and theoretical perspectives

Exposure to environmental risks before birth can harm foetal growth and contribute to negative health outcomes (WHO, 2002). A substantial body of research explores the impacts of prenatal exposure to adverse environmental conditions (Almond & Currie, 2011; Almond & Mazumder, 2011; Andalón et al., 2016; Camacho, 2008; Currie & Rossin-Slater, 2013; Dorélien, 2019; Torche, 2011). This body of research mainly focuses on the impact of climatic shocks on health at birth and throughout childhood, including birthweight, preterm birth, and malnutrition (Aguilar & Vicarelli, 2011; Andalón et al., 2016; Andriano, 2023; Cornwell & Inder, 2017; Davenport et al., 2020; Deschênes et al., 2009; Dimitrova, 2021; Dimitrova & Muttarak, 2020; Grace et al., 2015, 2021; Kumar et al., 2016; Rocha & Soares, 2015).

Research on prenatal exposure to weather shocks and early childhood mortality is still in its infancy. Only a few studies have analysed the effects of in-utero exposure to weather shocks on the mortality of infants, overlooking the effects extending into subsequent years of life. Kudamatsu et al. (2012) find that drought exposure during the two rainy seasons before birth increases the mortality of infants born during the hungry season in arid areas of Africa by 23.1 deaths per 1,000 live births, primarily attributed to maternal malnutrition. Flatø and Kotsadam (2014) find that extreme droughts occurring in the rainy season prior to birth in sub-Saharan Africa increase female infant mortality by 11.9 deaths per 1,000 live births, attributing this to gender-based discrimination occurring after birth. In a study from the semiarid Northeast Brazilian region, Rocha and Soares (2015) find that a drought episode 1 year before birth increases the infant mortality rate by 3.3 points, largely due to intestinal infections and malnutrition. Kumar et al. (2016) find that infant mortality increased by 3.5 deaths per 1,000 live births for children exposed to a drought during the year of birth, but no significant effects were found for in-utero exposure.

Although pinpointing the reasons for the divergent findings in previous studies is challenging, these studies offer insights into key pathways linking in-utero drought exposure to infant mortality—pathways that are relevant to this work on under-five mortality. These pathways, which I discuss in detail below, include maternal malnutrition, altered disease environment, and maternal stress.

Firstly, droughts decrease the quantity, quality, and variety of crops produced, often causing significant increases in food prices and reductions in disposable income. For example, during the 1991–1992 drought in Zimbabwe, food prices surged by 72% (Stern, 2006). Droughts can also affect livestock and milk production and even lead to the death of livestock (Webb & Reardon, 1992), further reducing income for households that rely on these animals. For instance, during the 1985 drought, 75% of the herds of the Fulbe pastoralists perished (de Bruijn, 1997). To cope with decreased food access and income, households may resort to consuming calorie-dense but nutrient-poor foods (Bloem et al., 2010). This dietary shift exacerbates micronutrient deficiencies in pregnant women, amplifying their existing vulnerabilities during a critical nutritional period (Gebremedhin & Enquselassie, 2011) and ultimately increasing child mortality rates (Schoeps et al., 2018).[1]

Secondly, droughts also modify the disease environment by compromising water availability and quality, increasing the risk of water-borne infections (De Waal, 1989; Rocha & Soares, 2015). During pregnancy, such conditions can lead to chronic diarrhoea and result in anaemia and micronutrient deficiencies that harm both maternal and new-born health (Chen et al., 2012; Watt & Chamberlain, 2011). Drought conditions also contribute to a rise in HIV prevalence among women, particularly due to an increase in transactional sex (Burke et al., 2014). This exchange of goods and cash for sexual relationships before and during pregnancy could increase the risk of HIV transmission from infected mothers to their children, subsequently increasing the risk of mortality in the absence of antiretroviral therapy (WHO, 2010).

Thirdly, droughts also induce maternal stress and increased energy expenditure. Stress during pregnancy is linked to the production of hormones and cortisol that are associated with preterm delivery (Glynn et al., 2001; Hobel, 2004; Lockwood, 1999), contributing to lower birthweight—a well-known risk factor of early childhood mortality. Drought conditions also often require women to travel greater distances to access clean water. Carrying heavy water loads could adversely affect women's health (Geere et al., 2010), compounding the risks associated with pregnancy.

Agriculture and climate in Côte d'Ivoire

Côte d'Ivoire, located in West Africa, has an economy heavily reliant on agriculture. The sector employs approximately two-thirds of the population and contributes significantly to the national GDP (FAO et al., 2018; Riquet et al., 2017). The primary agricultural products include cocoa, coffee, palm oil, and rubber, which are crucial export commodities. Subsistence farming is prevalent, with many households depending on the cultivation of staples such as rice, maize, cassava, and yams for their daily sustenance. In fact, 64% of Côte d'Ivoire's total area is comprised of arable land (FAO et al., 2018), underscoring the importance of agriculture for ensuring food security in the country.

The climate in Côte d'Ivoire is predominantly tropical, characterised by a humid equatorial zone in the southern regions and a tropical savannah climate in the northern regions. The country generally experiences a rainy season from June to October and average annual temperatures range from 24 to 28 °C (World Bank,

[1] Note that it is not necessary to be a food producer or livestock farmer to suffer from lower agricultural outputs because lower yields and reduced livestock production translate into higher prices for everyone. Similarly, families involved in the production of export crops in the country, such as cocoa and coffee, could financially suffer from lower yields which limit their overall purchasing power.

2021b). In the south, the climate allows for two growing seasons: the first starts between March and May and lasts until July, sometimes extending to October, while the second starts in August and ends in November/December. In the north, there is a single growing season from April/May to October/November, with season lengths ranging from 80 to 190 days (Goula et al., 2010).

Despite the favourable conditions for agriculture, the country's high dependence on subsistence farming and rainfed agriculture makes food security and general livelihood highly dependent on climatic conditions (FAO et al., 2018; World Bank, 2021a; Yapo et al., 2020). For instance, during periods of severe drought, the country has suffered substantial crop losses, undermining food security and negatively impacting the livelihoods of those dependent on farming (Côte d'Ivoire MINESUDD, 2014; FAO et al., 2018). Climate change poses potential threats to soil fertility, evaporation rates, and overall soil moisture content which may lead to diminished agricultural yields and production (World Bank, 2021a).

Demographic and socioeconomic vulnerabilities

In response to climate change, scholars and policymakers are increasingly looking for ways to mitigate the negative consequences of climate extremes. Individual- and community-level factors including the access to information, proximity to main roads, and capacity to diversify income can determine the extent to which climate extremes can disrupt livelihoods and affect children's survival chances. This line of thought aligns closely with the demographic differential vulnerability approach (Muttarak et al., 2015) which has been used to investigate how natural disasters and climate extremes can impact population groups differently depending on age, sex, socioeconomic status, and education (Andriano, 2023; Conte Keivabu & Cozzani, 2022; Dimitrova, 2021; Dimitrova & Muttarak, 2020).

When it comes to child mortality, research shows that women's education is an important determinant of children's survival chances: previous studies find a causal link between maternal education and child mortality (Andriano & Monden, 2019; Breierova & Duflo, 2004; Chou et al., 2010; Grépin & Bharadwaj, 2015; Makate & Makate, 2016). The literature also suggests that the relationship between maternal education and child survival chances persists during famines when food prices rise dramatically (Kiros & Hogan, 2000, 2001). Education is further found to both reduce vulnerability to weather shocks and increase the propensity to prepare against natural disaster (Hoffmann & Muttarak, 2017; Lutz et al., 2014).

Given the vast expansion in education in Côte d'Ivoire over the past few decades (UNESCO, 2015), education is particularly relevant in protecting against drought-related fatality in early childhood. Other potentially important factors for mitigating the negative consequences of drought exposure to under-five mortality include the child's sex, household wealth, and place of residence. In this study, I will investigate how in-utero exposure to agricultural droughts impacts the survival chances of children across different demographic and socioeconomic groups.

Data

I combine two sources of data: (1) three rounds of the Côte d'Ivoire Demographic and Health Survey (CDHS) georeferenced data on early childhood mortality and key demographic and socioeconomic characteristics, and (2) gridded climate data from the ERA-Interim (ERA-I) archive produced by the European Centre for Medium-Term Weather Forecasting (ECMWF). Each of these data sources is discussed in detail below.

Individual data

The individual-level data come from the CDHS rounds of 1994, 1998–1999, and 2011–2012. The DHS Program collects nationally representative data on population health, child mortality, and socioeconomic characteristics. Importantly for this study, the CDHS reports the GPS latitude and longitude coordinates of clusters where women and their children reside, which enables linking them to their geographic location at survey time.[2] I use their geographic location at survey time as a proxy for their geographic location during gestation. Using the latitude and longitude data in the DHS, I match each child to the weather grid cell corresponding to their location to construct variables of in-utero exposure to agricultural droughts.

The analytical sample includes children born in the 5 years prior to the survey, covering 13,545 children born to 10,275 mothers living in over 727 geographic locations (see Fig. 1 for a map of the geographic locations).

Climate data

The climate data used to calculate the variable for agricultural droughts, as measured by SPEI, are taken from the high-quality ERA-Interim reanalysis dataset (Dee et al., 2011). The ERA-Interim dataset contains information on climate for every 6 hours from 1 January 1979, on a global grid of parallels and meridians at a $0.75 \times 0.75°$ resolution (about 80 km by 80 km at the equator).[3] This dataset has been previously

[2] To preserve confidentiality, urban clusters are displaced a distance of up to 2 km; rural clusters up to 5 km. A randomly selected 1% of rural clusters are displaced a distance up to 10 km (Burgert et al., 2013). In this analysis, this random displacement is unlikely to pose a significant issue for two main reasons. Firstly, the climate data used in the study has a spatial resolution of 80 km by 80 km, meaning each grid cell covers a vast area. Therefore, displacement of 2, 5, or even 10 km is minor relative to the size of each grid cell, ensuring that most data points remain within the same climate grid cell despite being displaced. Secondly, the weather variability between neighbouring grid cells is minimal, suggesting that even if a displacement shifts a data point to an adjacent cell, the climatic conditions relevant to this analysis—such as temperature or rainfall patterns—remain substantially the same.

[3] The choice of the ERA-I dataset for analysis was driven by practical considerations. At the time of the analysis, the SPEI database developed by Vicente-Serrano and colleagues was only available up to the year 2006 (Vicente-Serrano, Beguería, López-Moreno, et al., 2010a, 2010b). Given that this analysis extends until 2012, the ERA-I dataset was the most viable option at that time, as it allowed for the calculation of the SPEI at a fine spatial resolution. While other datasets also offered this possibility, ERA-I, being reanalysis data, was deemed the optimal choice. Since then, newer and more spatially fine-grained reanalysis datasets such as ERA5 have become available, providing additional options for calculating the

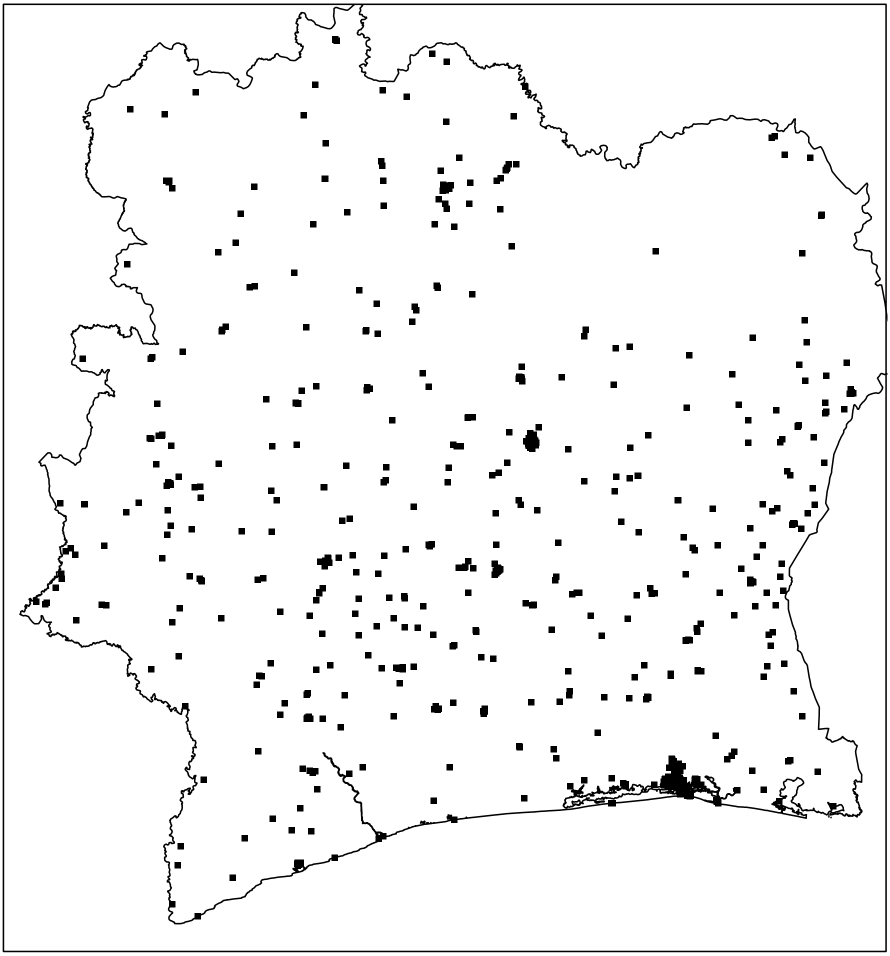

Fig. 1 Spatial distribution of DHS clusters across Côte d'Ivoire

used in studies exploring the effects of extreme weather on life-course transitions, infant mortality, and conflict incidence (Andriano & Behrman, 2020; Flatø & Kotsadam, 2014; Harari & La Ferrara, 2018).

In order to calculate SPEI, I use data up to April 2012[4] on monthly mean daily net solar radiation, monthly mean daily minimum and maximum temperatures, monthly mean daily wind speeds, monthly mean daily dewpoint temperature, elevation above

Footnote 3 (continued)
SPEI. Despite the evolving landscape of available datasets, the initial choice of ERA-I was guided by its compatibility with the specific requirements of the analysis at that time.

[4] April 2012 is the latest date of birth among children in the DHS sample.

sea level, latitude, and monthly total precipitation. I elaborate on how these weather parameters are used to calculate SPEI in the methods section below.

The advantages of the ERA-Interim data are that (i) they are reanalysed using various sources, such as satellites, radiosondes, pilot balloons, aircraft, wind profilers, ships, drifting buoys, and land stations,[5] and (ii) they have less bias in rainfall outcomes in the arid and semi-arid areas of Africa compared to gauge data (Zhang et al., 2013).

Empirical method

In-utero exposure to agricultural droughts as measured by SPEI

In this study, I introduce a novel measure of in-utero exposure to agricultural droughts, focusing primarily on its impact on maternal malnutrition during pregnancy. It is important to note that this measure does not isolate maternal malnutrition as the sole pathway through which agricultural droughts may affect early childhood mortality. For example, agricultural droughts could lead to maternal malnutrition which may impair a newborn's growth. Alternatively, this impaired growth itself can increase the newborn's susceptibility to infections, further impairing growth. This measure still offers an understanding of the broader effects of agricultural droughts on early childhood mortality.

To measure agricultural drought conditions, I use the SPEI. SPEI is a standardised, multiscalar index measuring drought severity, intensity, and duration. Unlike precipitation-based drought indices, it allows for comparisons of drought severity across space and time since it can be calculated over a wide range of climates (Vicente-Serrano et al., 2010a, b). The SPEI also has the advantage of being multiscalar, meaning it can be computed at different time scales over which water deficits accumulate to reflect different drought types. Short time scales refer to soil water content and river discharge, and long time scales relate to changes in groundwater storage (Vicente-Serrano et al., 2010a, b).

For this analysis, I use the SPEI at a 3-month time scale (SPEI3) because it reflects short- and medium-term moisture conditions, providing a seasonal estimation of climate relevant for agriculture (WMO, 2012). Agricultural droughts are associated with a shortage of water for plant growth and are characterised by insufficient soil moisture to replace evapotranspirative losses (WMO, 1975), which negatively affects crop production (Boken, 2005; Sivakumar et al., 2010; Wu et al., 2011). Several indices have been developed to measure agricultural droughts, but the SPEI has been identified as the most complete and robust agricultural drought

[5] Reanalysis data combine available observational data with model forecasts to create a comprehensive, consistent, and detailed historical record of atmospheric conditions (Zhang et al., 2013). This process ensures that the data provide 'a multivariate, spatially complete, and coherent record of the global atmospheric circulation' (Dee et al., 2011, p.554).

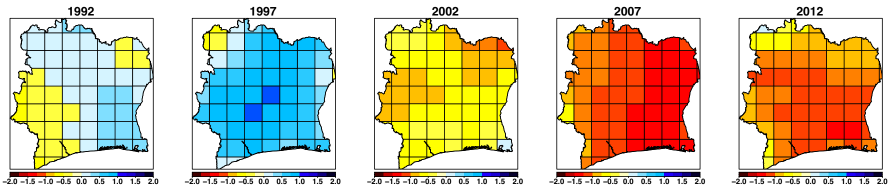

Fig. 2 Spatial distribution of SPEI3 across Côte d'Ivoire in 1992, 1997, 2002, 2007, and 2012

index in Africa (WMO, 2012) (see Sivakumar et al. (2010) for a review of all agricultural drought indices).

SPEI is expressed in units of standard deviation from the cell average and has mean 0 by construction, where negative values below -1 indicate dry conditions and positive values above $+1$ indicate wet conditions. Dry conditions can be categorised into moderately dry ($-1 \leq$ SPEI < -1.5), severely dry ($-1.5 \leq$ SPEI < -2), and extremely dry SPEI ≤ -2. Similarly, wet conditions are categorised into moderately wet $1 \leq$ SPEI < 1.5, very wet ($1.5 \leq$ SPEI < 2), and extremely wet (SPEI ≥ 2) (WMO, 2012). In additional analyses, I leverage these pre-established categorisations of SPEI to explore the effects of severe and extreme droughts (SPEI ≤ -1.5), which I refer to as severe droughts in the remainder of the paper.

To create the measure of in-utero exposure, I follow three steps. First, I use the monthly weather data to compute the potential evapotranspiration (PET), representing the amount of water that could be evaporated and transpired if a sufficient water source were available. This calculation is performed for each ERA-I cell and month up to April 2012. Second, I use the monthly PET and monthly total precipitation to derive the SPEI3 for each ERA-I cell and month up to April 2012.[6] (Additional information on all the weather parameters and calculations used for the derivation of PET and SPEI is available in the Supplementary Material.) In the third step, I calculate the average SPEI3 value during the 12 months preceding the child's date of birth. This measure based on SPEI3 likely captures the weather conditions affecting maternal nutrition during pregnancy.

Figure 2 shows the SPEI3 values across Côte d'Ivoire over time for the period of analysis between 1992 and 2012. The figure shows areas where SPEI3 values are negative (yellow to red squares) or positive (light blue to dark blue). The patterns observed in Fig. 2 are compatible with the historical records of drought in Côte d'Ivoire. For example, the data used for this analysis show that the country was hit by drought in 2007, an event caused by the delayed onset of the wet season (NASA, 2007).

[6] The R package 'SPEI' is used to generate monthly values of SPEI based on the input ERA-I data (Beguería & Vicente-Serrano, 2013).

Fixed-effects linear probability model

A fixed-effects linear probability model is used to investigate the effect of in-utero exposure to SPEI on under-five mortality. The model specification reads as follows:

$$p_{imygs} = \beta_1 \text{spei}_{myg} + \boldsymbol{x}_i \boldsymbol{\delta} + \boldsymbol{\alpha}_m + \boldsymbol{\alpha}_y + \boldsymbol{\alpha}_g + \boldsymbol{\alpha}_s + \varepsilon_{imygs} \quad (1)$$

where p_{imygs} is a binary variable for under-five mortality of child i born in month m and year y residing in ERA-I cell g from survey year s; spei_{myg} is the average SPEI3 value during the 12 months before the child's date of birth.[7] The vector of child, parental, and community characteristics, $\boldsymbol{x}_i$, includes child's sex, child's birth order (first birth; 2–4 births; 5 + births), maternal education attainment (no formal education; primary education; secondary and higher education), paternal education attainment (no formal education; primary education; secondary and higher education; missing/don't know; the 'missing/don't know' category implicitly describes a woman's marital status because the question about paternal education was not asked to women who were not in a union at the time of the survey), mother's age at birth, mother's age at birth squared, household wealth (wealthy or poor),[8] and place of residence (rural or urban).

The vectors of month-of-birth fixed effects, year-of-birth fixed effects, and ERA-I cell fixed effects are denoted as $\boldsymbol{\alpha}_m$, $\boldsymbol{\alpha}_y$, and $\boldsymbol{\alpha}_g$, respectively. The use of these fixed effects allows to account for ERA-I cell-specific, temporal, and seasonal trends, enabling a causal interpretation of estimates. The survey-year fixed effects, $\boldsymbol{\alpha}_s$, capture potential effects from pooling data across surveys, controlling for any unobserved differences between survey years which may bias the results such as survey design, implementation, and population characteristics. I also use survey-year weights, which adjust the data to reflect how many people were interviewed as a proportion of the population in that year.[9] This weighting ensures results are representative of the individuals living in Côte d'Ivoire over time (ICF International, 2012).

To investigate whether key demographic and socioeconomic factors can mitigate the effect of in-utero exposure to agricultural droughts on under-five mortality, I estimate a new set of fixed-effects linear probability models. These models include an interaction term between the variable of severe agricultural droughts and a categorical variable which captures the key demographic and socioeconomic factors. Population subgroups are distinguished by the child's sex, the mother's level of education, the father's level of education, the household wealth, and the place of residence. I also combine parents' level of education with household wealth

[7] To facilitate interpretation of results, the dependent variable was multiplied by 100.

[8] I use the DHS wealth index to classify households by their economic status. Wealthy households are in the highest three wealth quintiles; poor households are in the lowest two wealth quintiles.

[9] These weights are calculated as the ratio between the female population aged 15–49 in the country in the year of the survey and the number of women aged 15–49 interviewed in the survey, using population data from United Nations Population Division's World Population Prospects. For the CDHS 1998–1999, I use the average of the female population between 1998 and 1999; for the CDHS 2011–2012, I use the average of the female population between 2011 and 2012.

and place of residence into two categorical variables to pinpoint potential population subgroups most vulnerable to climatic shocks such as the lower educated and poor (Dimitrova & Muttarak, 2020). The first categorical variable has the following categories: 'no formal education and poor', including children whose parents have no formal education and whose households are in the lowest two wealth quintiles; 'formal education and poor', including children whose parents have at least primary education and whose households are in the lowest two wealth quintiles; 'no formal education and wealthy', including children whose parents have no formal education and whose households are in the highest three wealth quintiles; and 'formal education and wealthy', including children whose parents have at least primary education and whose households are in the highest three wealth quintiles. The second categorical variable has the following categories: 'no formal education and rural'; 'formal education and rural'; 'no formal education and urban'; and 'formal education and urban'.

Results

Descriptive statistics

Table 1 presents the summary statistics of the variables used in this analysis for the overall sample and by survey. The average under-five mortality rate in the sample is 10.4%, increasing from 8.6% in 1994 to 14.2% in 1998–1999 and then decreasing to 8.2% in 2011–2012, a trend in line with other national estimates (Garenne & Gakusi, 2005). Children in the sample are evenly distributed by sex and born to mothers aged 26 years on average. The percentage of children varies by birth order, with 22.4% being firstborn, 46.9% being of birth order 2–4, and 30.7% being of birth order 5 or higher. 64.7% of the children live in rural areas, and 45% are born in poor households. A large percentage of children have parents with no formal education. Notably, more than 19% of children were exposed to severe agricultural droughts during gestation.[10] This relatively high prevalence of drought exposure highlights the importance of investigating potential health outcomes associated with severe agricultural droughts.

Main model results

Table 2 shows the results of the model described in Eq. (1).[11] Due to significantly higher under-five mortality in the 1998–1999 survey, primarily attributable to HIV/AIDS (Garenne & Gakusi, 2005), and the relatively low prevalence of

[10] This exposure rate varies significantly over time, with 5.31% in 1994, 3.16% in 1998–1999, and a peak of 37.28% in 2011–2012. These variations could be attributed to increases in the prevalence of droughts in more recent years or specific conditions unique to each year.

[11] For simplicity, only coefficients of SPEI are reported; full results for the specification are available upon request.

Table 1 Sample characteristics

Characteristic	$N = 13{,}545$[a]	$N^{1994} = 3{,}998$	$N^{1998–1999} = 1{,}992$	$N^{2011–2012} = 7{,}555$
Under-five mortality rate (per 100)	10.4 (30.5)	8.6 (28.1)	14.2 (34.9)	8.2 (27.5)
Average SPEI3	−0.1 (0.8)	0.3 (0.3)	0.6 (0.5)	−0.8 (0.4)
Severe droughts	19.4%	5.3%	3.2%	37.3%
Very wet conditions	10.4%	0.5%	29.4%	0.2%
Sex				
Female	49.9%	49.3%	50.0%	49.9%
Male	50.2%	50.7%	50.0%	50.1%
Child's birth order				
1	22.4%	20.1%	23.6%	22.5%
2–4	46.9%	44.8%	44.6%	49.6%
5+	30.7%	35.1%	31.8%	28.0%
Mother's education				
No education	64.7%	66.3%	65.2%	63.6%
Primary education	26.4%	24.9%	27.5%	26.1%
Secondary and higher education	9.0%	8.7%	7.3%	10.3%
Father's education				
No education	30.8%	47.5%	0%	46.8%
Primary education	12.3%	17.7%	0%	19.2%
Secondary and higher education	13.1%	20.2%	0%	19.9%
Missing/don't know	43.9%	14.6%	100.00%	14.1%
Mother's age at birth	26.0 (6.9)	25.8 (6.9)	25.9 (7.1)	26.1 (6.8)
Type of residence				
Rural	64.7%	66.2%	68.1%	61.6%
Urban	35.3%	33.8%	31.9%	38.4%
Type of household				
Poor	45.0%	43.6%	46.8%	44.1%
Wealthy	55.1%	56.4%	53.2%	55.9%

[a]Means and percentages are based on weighted data, standard errors in parenthesis; *N* is unweighted. For column 2, the weights are the survey-specific sampling weights multiplied the survey-year weights, where the survey-year weights are calculated as the ratio between the woman's female population 15–49 in the country in the year of the survey and the number of women 15–49 interviewed in the survey (ICF International, 2012). For columns 3–5, the weights are the survey-specific sampling weights. The variable for the father's level of education is missing in the DHS 1998–1999

drought exposure among children in the survey, I have excluded children from the 1998–1999 survey from the main analysis. This exclusion is intended to enhance the efficiency of the estimator. It is worth noting that the results remain consistent even when children from the 1998–1999 survey are included (Table 1 in the Supplementary Material).

Findings suggest that SPEI3 is negatively linked to under-five mortality (Model 1). A one-unit decrease in SPEI3 is associated with a 3.4 percentage point increase in the probability that a child dies before the age of five, an effect

Table 2 Effect of SPEI3 on under-five mortality

	All	All	All
	Model 1	Model 2	Model 3
Average SPEI3 ($t-1$)	−3.389**	−4.945**	−3.330**
	(1.138)	(1.468)	(1.149)
Average SPEI3 ($t-2$)		−1.482	
		(0.989)	
Average SPEI3 ($t-1$), squared			−0.834
			(1.018)
Control variables	Yes	Yes	Yes
Grid-cell FEs	Yes	Yes	Yes
Month-of-birth FEs	Yes	Yes	Yes
Year-of-birth FEs	Yes	Yes	Yes
Survey-year FEs	Yes	Yes	Yes
N	11,553	11,553	11,553

$^{+}p<.1$; $^{*}p<.05$; $^{**}p<.01$; $^{***}p<.001$

Control variables: maternal education, paternal education, household wealth, child's sex, child's birth order, place of residence, mother's age at birth, mother's age at birth squared, ERA-I grid-cell fixed effects, month-of-birth fixed effects, year-of-birth fixed effects, and survey-year fixed effects. Standard errors are clustered by ERA-I grid cell

that is significant at the 1% level and that corresponds to a 41% increase in the under-five mortality rate given an average mortality rate of 8.4%.

In the next analysis I investigate whether more recent in-utero exposure to agricultural dry conditions should have larger or smaller effects on under-five mortality than less recent one. This analysis helps disentangle the stage in pregnancy in which drought influences under-five mortality. In particular, a less recent drought would affect intrauterine growth around conception and in the first period of pregnancy (i.e. embryogenesis and initial foetal development), as opposed to a more recent drought that would influence intrauterine growth during the final foetal period.

I therefore calculate SPEI3 in the 12-to-24-month period before birth to measure less recent in-utero exposure to agricultural dry conditions and add it to the model. The coefficients presented in Model 2, Table 2, indicate that SPEI3 is negatively linked to under-five mortality; however, this negative relationship is statistically significant for more recent exposure, while the coefficient for less recent exposure is also negative but not statistically significant. This finding suggests that exposure to agricultural dry conditions during the final foetal period is detrimental to the survival chances of children. The most plausible explanation for this finding is that we are capturing a nutrition effect given that maternal nutritional shocks primarily impact foetal growth during the later stages of gestation (Darling, 2017; Lawton et al., 1988; Lumey, 1998; Painter et al., 2005; Strauss & Dietz, 1999).

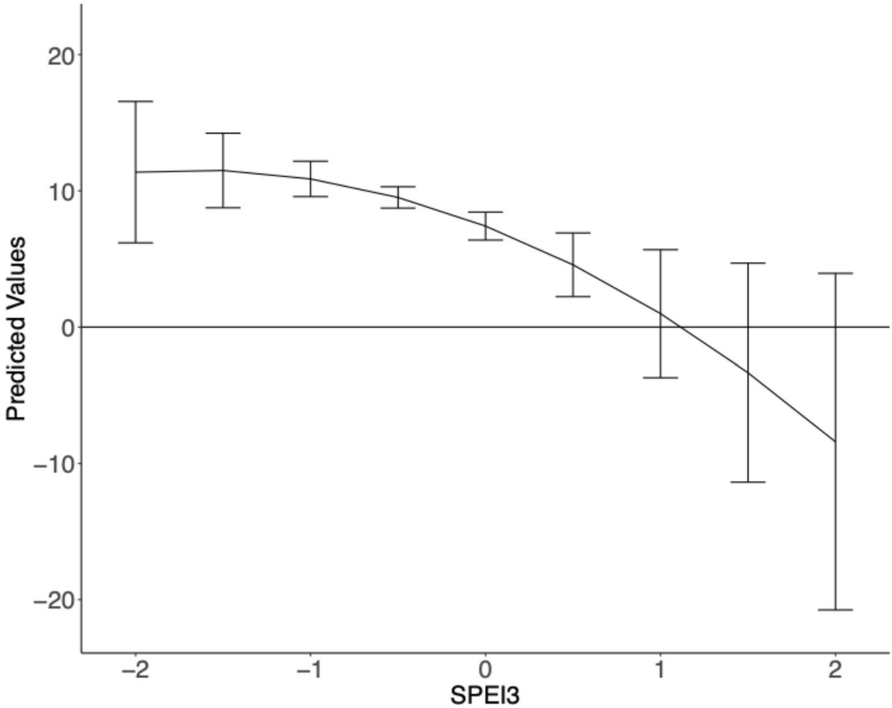

Fig. 3 Predicted values of under-five mortality at varying levels of SPEI3. Notes: The model controls for maternal education, paternal education, household wealth, child's sex, child's birth order, place of residence, mother's age at birth, mother's age at birth squared, ERA-I grid-cell fixed effects, month-of-birth fixed effects, year-of-birth fixed effects, and survey-year fixed effects. Standard errors are clustered by ERA-I grid cell

Exploring non-linear relationships

I next investigate potential non-linear relationships between SPEI3 and under-five mortality. For this analysis, I include the quadratic polynomial of the SPEI3 variable in the regression model (Model 3, Table 2). Figure 3 shows the predicted values of under-five mortality at different levels of SPEI3 derived from this model.

The results indicate children exposed to droughts in-utero are considerably more likely to die. As SPEI3 decreases from 0 to − 1.5, the probability that a child dies before the age of five rises from 7.4 to 11.5%, *ceteris paribus*. Importantly, the data also shows that the risk of mortality decreases at positive values of SPEI (≥ 2), but the estimates are imprecise, as indicated by wide confidence intervals.[12] Such extreme SPEI values indicate exposure to very wet conditions. While climatic shocks often have negative consequences for local livelihoods, there are also instances when climatic shocks could be beneficial for livelihoods. A study in Senegal found

[12] This is likely due to the small percentage of children exposed to very wet conditions in-utero in the sample (i.e. 0.32%).

that positive rainfall shocks reduced infant mortality, suggesting a positive income shocks and food supply from a plentiful harvest (Pitt & Sigle, 1998).

Severe drought conditions

I next investigate the impact of in-utero exposure to droughts on under-five mortality. I classify a child as being exposed to 'severe agricultural droughts' in-utero if the average SPEI3 value during the 12 months before the child's date of birth is ≤ -1.5, and as 'non-droughts' otherwise.

The results shown in Table 3 indicate that in-utero exposure to severe agricultural droughts significantly increases under-five mortality (Model 1). Specifically, being exposed to severe agricultural droughts is associated with a 2.3 percentage point increase in the probability that a child dies before the age of five, which corresponds to a 28% increase in the under-five mortality rate given an average mortality rate of 8.4%. Again, I only find evidence of a relationship between more recent droughts and under-five mortality (Model 2), and no significant relationship is found between exposure to very wet conditions and under-five mortality (Models 1 and 2).

Table 3 Effect of severe agricultural droughts on under-five mortality

	All	All	Low conflict affected areas
	Model 1	Model 2	Model 3
Severe droughts ($t-1$)	2.344**	2.350**	3.061**
	(0.785)	(0.778)	(1.070)
Severe droughts ($t-2$)		0.433	
		(0.702)	
Very wet conditions ($t-1$)	−2.122	−1.825	−5.607
	(3.187)	(3.259)	(3.752)
Very wet conditions ($t-2$)		1.894	
		(2.883)	
Control variables	Yes	Yes	Yes
Grid-cell FEs	Yes	Yes	Yes
Month-of-birth FEs	Yes	Yes	Yes
Year-of-birth FEs	Yes	Yes	Yes
Survey-year FEs	Yes	Yes	Yes
N	11,553	11,553	6,629

$^{+}p<.1$; $^{*}p<.05$; $^{**}p<.01$; $^{***}p<.001$

Control variables: maternal education, paternal education, household wealth, child's sex, child's birth order, place of residence, mother's age at birth, mother's age at birth squared, ERA-I grid-cell fixed effects, month-of-birth fixed effects, year-of-birth fixed effects, and survey-year fixed effects. Standard errors are clustered by ERA-I grid cell

In the next analysis, I examine the impact of in-utero exposure to severe agricultural droughts on infant mortality to understand whether previous studies may have underestimated the impact of droughts on early childhood mortality (Table 4). My findings indicate that droughts are positively linked to infant mortality, but the effect is not statistically significant (Model 1). I then explore the impact on child mortality, defined as death between 12 and 59 months old, and find that the impact is positive and significant (Model 2). These findings suggest that the detrimental effects of in-utero drought exposure may manifest more significantly as children grow older, perhaps due to impaired growth in-utero that increases their susceptibility to infections and diseases as they grow.

Robustness checks

I now provide a detailed discussion about the several potential channels that may bias this effect. One potential source of bias in the estimate is selection in-utero. If a weaker foetus is more likely to die in-utero due to drought exposure, then the stronger foetuses are more likely to survive. Previous research finds that maternal exposure to climate extremes increases pregnancy loss (Davenport et al., 2020). It is worth noting that this will likely underestimate the true effect of in-utero exposure to agricultural droughts on early childhood mortality.

Another source of bias is migration after conception. Because the DHS data contain women's geographic location at survey time, it is difficult to determine that women and children are exposed to the weather conditions in the same area (i.e. ERA-I grid cell) in the 12 months before birth. The direction of the bias is unclear.

Table 4 Effect of severe agricultural droughts on infant and child mortality

	Infant mortality	Child mortality
	Model 1	Model 2
Severe droughts	1.084	1.260**
	(0.730)	(0.366)
Very wet conditions	−0.640	−1.482
	(2.522)	(1.192)
Control variables	Yes	Yes
Grid-cell FEs	Yes	Yes
Month-of-birth FEs	Yes	Yes
Year-of-birth FEs	Yes	Yes
Survey-year FEs	Yes	Yes
N	11,553	11,553

$^{+}p<.1$; $^{*}p<.05$; $^{**}p<.01$; $^{***}p<.001$

Control variables: maternal education, paternal education, household wealth, child's sex, child's birth order, place of residence, mother's age at birth, mother's age at birth squared, ERA-I grid-cell fixed effects, month-of-birth fixed effects, year-of-birth fixed effects, and survey-year fixed effects. Standard errors are clustered by ERA-I grid cell

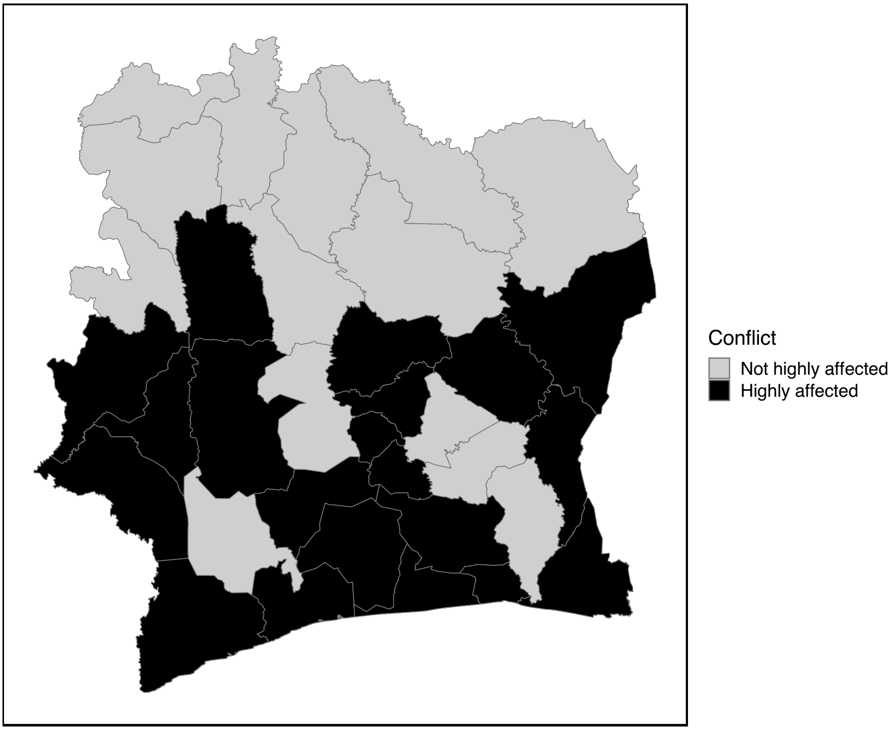

Fig. 4 Exposure to conflict across areas of Côte d'Ivoire, 1997–2012. Notes: The map includes all conflict events available in the xSub repository and defines as 'highly affected' if there were more than two conflict events in that area. The choice of two as the threshold is based on it being the median in the sample

For example, if a woman moves to an area with more favourable climatic conditions within the year preceding her child's birth and the time of the survey, the estimate may potentially underestimate the true impact of in-utero exposure to agricultural drought on early childhood mortality.

Unfortunately, the CDHS does not contain information on women's migration history.[13] The country experienced significant displacement as a result of the political instability between 1999 and 2011. The conflict, however, varied widely across the country, and some regions were more affected by the conflict than others. I use spatial data on conflict available from xSub (Zhukov et al., 2019), a repository of microlevel, subnational event data on armed conflict and contention to be able to identify the areas that were most affected by conflict in the 2000s. Figure 4 shows that the western, eastern, southern, and to a lesser extent the central parts of the country were most affected. I therefore estimate the same model excluding children living in areas that were highly affected by the conflict, that is, all children from

[13] Only in the 1994 CDHS survey were women asked whether they always lived in their current residence and how many years they had lived there.

the 2012 DHS living in 19 regions. Excluding children living in the highly affected areas from the sample does not change the sign and significance level of the coefficient (Model 3, Table 3). If anything, the magnitude of the coefficient increases, suggesting a potential underestimation of the true effect of in-utero exposure to agricultural drought on under-five mortality.

Identifying vulnerable groups of the population

In the following analysis, the empirical model is extended by including an interaction term between the droughts variable and key demographic and socioeconomic factors. Above, I identified that droughts in the 12 months prior to birth are critical to child survival. I therefore focus on droughts experienced during this timeframe.

Figure 5 shows the results of the models with an interaction term. First, gender differences in climate-related vulnerability can be observed: droughts are associated with an increased risk of mortality for boys, while marginally significant effects for girls are found (Model 1). This disparity can be attributed to male vulnerability in early life (DiPietro & Voegtline, 2017), particularly related to nutritional factors.

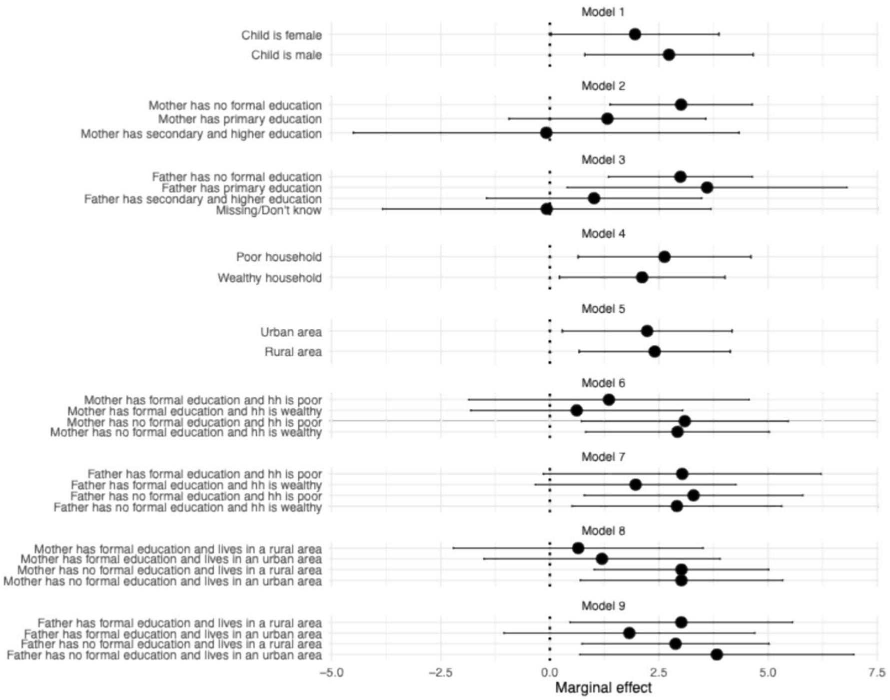

Fig. 5 Marginal effects of severe agricultural droughts on under-five mortality by demographic and socioeconomic groups. Notes: All models also control for child's birth order, mother's age at birth, mother's age at birth squared, very wet conditions, ERA-I grid-cell fixed effects, month-of-birth fixed effects, year-of-birth fixed effects, and survey-year fixed effects. Standard errors are clustered by ERA-I grid cell

Male foetuses generally have higher growth rates, which result in greater nutritional demands. During droughts, the reduced availability of nutrients can disproportionately affect male foetuses, making them more susceptible to health issues later in childhood.

Second, the results show that children born to less educated mothers, regardless of the family's wealth status, are particularly susceptible to mortality due to drought exposure (Model 6). Interestingly, there is no evidence that higher wealth status provides the same level of protection as maternal education (Models 4 and 6). The negative consequences of in-utero exposure to severe agricultural droughts are mainly concentrated among children whose mothers have no formal education.

One plausible explanation for the finding that maternal education mitigates the effects of in-utero exposure to droughts on under-five mortality regardless of the family's wealth status is that highly educated mothers typically reside in urban areas. In urban areas, they may benefit from less direct dependence on agriculture and better access to diverse nutritional options, which can improve their ability to manage risks associated with droughts during pregnancy. They may also have greater access to information and support services, important for maintaining health during drought conditions. However, this is not what my findings suggest. I find no evidence that urban living shields children from drought-related mortality (Models 5 and 8). The negative impact of agricultural drought on under-five mortality is statistically insignificant for children of highly educated mothers, regardless of whether they live in rural or urban areas, yet remains significant for children of less educated mothers in both settings (Model 8). These findings suggest that the protective effects of maternal education against the impacts of droughts on under-five mortality are not dependent on the context in which mothers live. They could instead be linked to the specific knowledge, behaviours, and practices that highly educated mothers employ.[14]

Father's education seems to protect against drought-related mortality in a similar way as mother's education. As expected, children born to less educated and poor fathers are the most vulnerable (Model 7). Interestingly, the protective effect of paternal education is only evident in urban settings, where the impact of in-utero exposure to droughts on under-five mortality is statistically insignificant (Model 9). Unlike for mothers, the benefits of education for fathers are more context dependent. In urban settings, access to diverse and stable job markets that are less affected by environmental shocks may amplify the benefits of paternal education, allowing fathers to better support their families.

[14] It could also be that women with higher education are less likely to live in drought-prone areas, where exposure to agricultural droughts is disproportionately higher. In a supplementary analysis, I find that mothers who are pregnant during droughts do not have higher education (Table 2 in the Supplementary Material).

Discussion and conclusion

In this study I investigated the impact of in-utero exposure to agricultural droughts on under-five mortality in Côte d'Ivoire, a country highly dependent on rainfed agriculture where weather fluctuations heavily influence crop productivity and food access (World Bank, 2021a). I linked survey data with local climate data to create a measure of agricultural droughts during gestation. While this analysis spans 18 years and does not fully account for all temporal changes in technology and infrastructure potentially impacting drought resilience and coping mechanisms, the findings reveal that in-utero exposure to severe agricultural droughts is associated with increases in the risk of mortality. By extending the focus to include under-five mortality, this study also suggests that previous research might have underestimated the effect of drought on early childhood mortality (Flatø & Kotsadam, 2014; Kudamatsu et al., 2012; Kumar et al., 2016; Rocha & Soares, 2015). I find that most recent droughts seem to exert the greatest impact suggesting that the final foetal period is crucial for interventions aimed at mitigating adverse health outcomes. This increased vulnerability during the final foetal period is likely due to the critical role of maternal nutrition during this stage (Lawton et al., 1988; Lumey, 1998; Painter et al., 2005; Strauss & Dietz, 1999), impacting foetal growth and subsequent child health.

This work underscores the increasing challenge of securing children's survival chances amidst projected rises in droughts in the region (AfDB, 2018; World Bank, 2021a; Yapo et al., 2020). Identifying the most vulnerable groups is crucial for developing targeted interventions. The analysis revealed that boys are particularly vulnerable to in-utero drought exposure, likely due to their higher nutritional demands during foetal development. This finding contrasts with some previous studies (Flatø & Kotsadam, 2014) but aligns with others that highlight boys' increased vulnerability to climatic shocks (Andriano, 2023; Dimitrova, 2021). Whether this increased vulnerability stems from behavioural factors, such as feeding practices favouring girls after birth, or biological reasons that render boys more susceptible to malnutrition during droughts falls beyond the scope of this paper. Nevertheless, my finding suggests that drought exposure in-utero is likely to amplify the already existing male survival disadvantage.

Parental education emerged as a critical protective factor against drought-related under-five mortality. Maternal education mitigates the adverse effects of droughts on under-five survival. This finding aligns with prior research emphasising the role of maternal education in improving children's health outcomes during climate extremes (Andriano, 2023; Dimitrova, 2021; Dimitrova & Muttarak, 2020), independent of economic status and living environments. Additionally, the protective effect of paternal education is significant, particularly in urban settings. This context-dependent benefit may be due to greater access to diverse and stable job markets, allowing fathers to better support their families during environmental shocks. Children born into lower educated and poor families are the most vulnerable to in-utero drought exposure, highlighting the compounded risk factors of lower education and poverty.

Some limitations should be noted. First, the mechanisms through which droughts increase under-five mortality are not directly identified. Because the core independent variable measures agricultural droughts rather than droughts that are not as directly tied to nutritional shocks, it is plausible that maternal malnutrition drives the effect of droughts on under-five mortality. This interpretation is corroborated by the finding that the effect of agricultural droughts is concentrated among boys and the final foetal period. This potential conclusion is consistent with previous research highlighting that poorer child health outcomes are driven by maternal nutritional shocks during pregnancy (Kudamatsu et al., 2012; Kumar et al., 2016). However, there could be other possible explanations; for example, droughts may also lead to an altered disease environment and increased maternal stress, impacting child survival chances. These possibilities were not possible to assess in the data but would be a fruitful area for future research.

Second, the sample might be biased due to (i) selective foetal loss, where weaker foetuses are more likely to die in-utero during droughts, and (ii) the cross-sectional nature of the data, which does not observe under-five children who may die after the survey. Both factors contribute to an underestimation of the true impact of droughts on under-five mortality.

Finally, the channels through which parental education mitigates the impacts of droughts on under-five mortality are not identified. The finding that the protective effects of maternal education against drought-related under-five mortality are not linked to economic status or living in rural areas suggests that the benefits arise from highly educated mothers possessing knowledge, adopting behaviours, and engaging in practices that enhance their ability to manage risks associated with droughts. This aligns with previous research highlighting that individuals with higher education are more likely to adopt preventive measures, which improves their ability to prepare for, cope with, and recover from the impacts of weather disasters (Helgeson et al., 2013; Hoffmann & Muttarak, 2017; Lutz et al., 2014; Muttarak & Pothisiri, 2013). Whether they are more conscious of the risks and better able to implement preventive measures is difficult to assess, especially since droughts are unexpected events and thus difficult to anticipate. Maternal education is also shown to enhance health knowledge and the utilisation of healthcare services during weather shocks, such as floods (Dimitrova & Muttarak, 2020). Future studies should examine specific behaviours and practices that contribute to this resilience to the impacts of droughts among children of highly educated mothers.

While this is a case study of Côte d'Ivoire, the findings carry important lessons for other low- and middle-income countries in sub-Saharan Africa. Specifically, the findings emphasise the need for policies that enhance educational opportunities for parents and develop targeted interventions for boys and children from families with little formal education. More broadly, this study contributes to better understanding the relationship between extreme climate and vital demographic outcomes. By better understanding the impact of climate extreme on early childhood mortality, the results help to put into perspective the impact of climate extremes on the health of surviving children. For example, studies reporting limited effect of drought on nutritional outcomes of surviving children should consider the possibility that droughts might exert an impact on early childhood mortality before concluding that agricultural shocks do not have determinantal effects on children's health.

Climate extremes pose a particular challenge to sub-Saharan Africa, where rainfed agriculture provides about 90% of the food and feed (Rosegrant et al., 2002) and diversification in rural income-generating activities is lower than in other regions (Davis et al., 2010). Agriculture serves as the primary source of livelihood for over 70% of the population and contributes to about 25% of GDP (Dixon et al., 2001; Hellmuth et al., 2007), which makes the region highly vulnerable to climate change (Boko et al., 2007; Collier et al., 2008; Esikuri, 2005). During the last decades, the region has witnessed an intensification of droughts in frequency, intensity, and geospatial coverage due to climate change (Collier et al., 2008; Masih et al., 2014). As drought can cause crop failure and food shortage that significantly impact children, understanding the relationship between extreme climate and vital demographic outcomes is crucial for developing effective adaptation strategies.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11111-024-00469-0.

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Data availability The raw individual data for this article is available for download from the DHS Program at https://dhsprogram.com. For the climate data, visit https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-interim.

Declarations

Conflict of interest The author declares no competing interests.

References

AfDB (2018). *National climate change profile: Côte d'Ivoire*. African Development Bank Group.

Aguilar, A., & Vicarelli, M. (2011). *El Nino and Mexican children: Medium-term effects of early-life weather shocks on cognitive and health outcomes*. Unpublished manuscript. http://www.aguilaresteva.com/wp-content/uploads/2012/09/El_Nino_Effects_Child_Dev_v17Nov11.pdf

Almond, D., & Currie, J. (2011). Killing me softly: The fetal origins hypothesis. *Journal of Economic Perspectives, 25*(3), 153–172. https://doi.org/10.1257/jep.25.3.153

Almond, D., & Mazumder, B. (2011). Health capital and the prenatal environment: The effect of Ramadan observance during pregnancy. *American Economic Journal: Applied Economics, 3*(4), 56–85.

Andalón, M., Azevedo, J. P., Rodríguez-Castelán, C., Sanfelice, V., & Valderrama-González, D. (2016). Weather shocks and health at birth in Colombia. *World Development, 82*, 69–82. https://doi.org/10.1016/J.WORLDDEV.2016.01.015

Andriano, L. (2023). On the health impacts of climatic shocks: How heatwaves reduce birthweight in sub-Saharan Africa. *Population and Development Review, 49*(4), 737–769. https://doi.org/10.1111/padr.12583

Andriano, L., & Behrman, J. (2020). The effects of growing-season drought on young women's life course transitions in a sub-Saharan context. *Population Studies, 74*(3), 331–350. https://doi.org/10.1080/00324728.2020.1819551

Andriano, L., & Monden, C. W. S. (2019). The causal effect of maternal education on child mortality: Evidence from a quasi-experiment in Malawi and Uganda. *Demography, 56*(5), 1765–1790.

Beguería, S., & Vicente-Serrano, S. M. (2013). SPEI: Calculation of the standardised precipitation-evapotranspiration index. *R Package Version, 1*, 6.

Bloem, M. W., Semba, R. D., & Kraemer, K. (2010). Castel Gandolfo workshop: An introduction to the impact of climate change, the economic crisis, and the increase in the food prices on malnutrition. *Journal of Nutrition, 140*(1), 132S-135S. https://doi.org/10.3945/jn.109.112094

Boken, V. K. (2005). Agricultural drought and its monitoring and prediction: Some concepts. In V. K. Boken, A. P. Cracknell, & R. L. Heathcote (Eds.), *Monitoring and predicting agricultural drought: A global study* (pp. 3–10). https://doi.org/10.1093/oso/9780195162349.001.0001

Boko, M., Niang, I., Nyong, A., Vogel, C., Githeko, A., Medany, M., Osman-Elasha, B., Tabo, R., & Yanda, P. (2007). Africa. Climate change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. In M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, & C. E. Hanson (Eds.), *Climate change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 433–467). Cambridge University Press. https://doi.org/10.2134/jeq2008.0015br

Breierova, L., & Duflo, E. (2004). *The impact of education on fertility and child mortality: Do fathers really matter less than mothers?* NBER (National Bureau of Economic Research) Working Paper 10513.

Burgert, C. R., Colston, J., Roy, T., & Zachary, B. (2013). *Geographic displacement procedure and georeferenced data release policy for the Demographic and Health Surveys*. https://doi.org/10.13140/RG.2.1.4887.6563

Burke, M., Gong, E., & Jones, K. (2014). Income shocks and HIV in Africa. *The Economic Journal, 125*, 1157–1189. https://doi.org/10.1111/ecoj.12149

Camacho, A. (2008). Stress and birth weight: Evidence from terrorist attacks. *The American Economic Review, 98*(2), 511–515.

Chen, J. Y., Ribaudo, H. J., Souda, S., Parekh, N., Ogwu, A., Lockman, S., Powis, K., Dryden-Peterson, S., Creek, T., Jimbo, W., Madidimalo, T., Makhema, J., Essex, M., & Shapiro, R. L. (2012). Highly active antiretroviral therapy and adverse birth outcomes among HIV-infected women in Botswana. *Journal of Infectious Diseases, 206*(11), 1695–1705. https://doi.org/10.1093/infdis/jis553

Chou, S.-Y., Liu, J.-T., Grossman, M., & Joyce, T. (2010). Parental education and child health: Evidence from a natural experiment in Taiwan. *American Economic Journal: Applied Economics, 2*(1), 33–61.

Collier, P., Conway, G., & Venables, T. (2008). Climate change and Africa. *Oxford Review of Economic Policy, 24*(2), 337–353.

Conte Keivabu, R., & Cozzani, M. (2022).Extreme heat, birth outcomes, and socioeconomic heterogeneity. *Demography*. https://doi.org/10.1215/00703370-10174836

Cornwell, K., & Inder, B. (2017). Child health and rainfall in early life. *The Journal of Development Studies, 51*(7), 865–880. https://doi.org/10.1080/00220388.2014.976618

Côte d'Ivoire MINESUDD (2014). Document de stratégie nationale de lutte contre les changements climatiques (2015–2020). Programme National Changement Climatique, Direction Générale de l'Environnement, Ministère de l'Environnement, de la Salubrité Urbaine et du Développement Durable.

Currie, J., & Rossin-Slater, M. (2013). Weathering the storm: Hurricanes and birth outcomes. *Journal of Health Economics, 32*(3), 487–503. https://doi.org/10.1016/j.jhealeco.2013.01.004

Darling, A. M. (2017). *Gestational weight gain and birth outcomes in US and Tanzanian populations*. PhD Thesis. Boston University.

Davenport, F., Dorélien, A., & Grace, K. (2020). Investigating the linkages between pregnancy outcomes and climate in sub-Saharan Africa. *Population and Environment, 41*(4), 397–421. https://doi.org/10.1007/s11111-020-00342-w

Davis, B., Winters, P., Carletto, G., Covarrubias, K., Quiñones, E. J., Zezza, A., Stamoulis, K., Azzarri, C., & DiGiuseppe, S. (2010). A cross-country comparison of rural income generating activities. *World Development, 38*(1), 48–63. https://doi.org/10.1016/j.worlddev.2009.01.003

de Bruijn, M. (1997). The hearthhold in pastoral Fulbe society, central Mali: Social relations, milk and drought. *Africa, 67*(4), 625–651. https://doi.org/10.2307/1161111
De Waal, A. (1989). Famine mortality: A case study of Darfur, Sudan 1984–5. *Population Studies, 43*(1), 5–24. https://doi.org/10.1080/0032472031000143826
Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A. C. M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., … Vitart, F. (2011). The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, *137*(656), 553–597. https://doi.org/10.1002/qj.828
Deschênes, O., Greenstone, M., & Guryan, J. (2009). Climate change and birth weight. *The American Economic Review, 99*(2), 211–217.
Dimitrova, A. (2021). Seasonal droughts and the risk of childhood undernutrition in Ethiopia. *World Development, 141*, 105417. https://doi.org/10.1016/j.worlddev.2021.105417
Dimitrova, A., & Muttarak, R. (2020). After the floods: Differential impacts of rainfall anomalies on child stunting in India. *Global Environmental Change, 64*, 102130. https://doi.org/10.1016/J.GLOENVCHA.2020.102130
DiPietro, J. A., & Voegtline, K. M. (2017). The gestational foundation of sex differences in development and vulnerability. *Neuroscience, 342*, 4–20. https://doi.org/10.1016/j.neuroscience.2015.07.068
Dixon, J., Gulliver, A., & Gibbon, D. (2001). *Farming systems and poverty: Improving farmers' livelihoods in a changing world*. FAO and World Bank.
Dorélien, A. (2019). The effects of in-utero exposure to influenza on birth and infant outcomes in the US. *Population and Development Review*, *0*(0), 1–35. https://doi.org/10.1111/padr.12232
Esikuri, E. E. (2005). *Mitigating drought — Long-term planning to reduce vulnerability*. Environment Strategy Notes; No. 13. World Bank. http://documents.worldbank.org/curated/en/291381468316145285/Mitigating-drought-long-term-planning-to-reduce-vulnerability
FAO, ICRISAT, & CIAT. (2018). *Climate-smart agriculture in Côte d'Ivoire.* CSA Country Profiles for Africa Series. InternationalCenter for Tropical Agriculture (CIAT); International Crops Research Institute for the Semi-Arid Tropics (ICRISAT); Food andAgriculture Organization of the United Nations (FAO), p 23.
Flatø, M., & Kotsadam, A. (2014). *Droughts and gender bias in infant mortality in sub-Saharan Africa*. Memorandum, No. 02/2014, University of Oslo, Department of Economics. http://hdl.handle.net/10419/102055
Garenne, M., & Gakusi, E. (2005). *Under-five mortality trends in Africa: Reconstruction from demographic sample surveys.* DHS Working Papers No. 26. ORC Macro.
Gebremedhin, S., & Enquselassie, F. (2011). Correlates of anemia among women of reproductive age in Ethiopia: Evidence from Ethiopian DHS 2005. *Ethiopian Journal of Health Development, 25*(1), 22–30. https://doi.org/10.4314/ejhd.v25i1.69842
Geere, J.-A.L., Hunter, P. R., & Jagals, P. (2010). Domestic water carrying and its implications for health: A review and mixed methods pilot study in Limpopo Province South Africa. *Environmental Health, 9*(1), 52. https://doi.org/10.1186/1476-069X-9-52
Glynn, L. M., Wadhwa, P. D., Dunkel-Schetter, C., Chicz-DeMet, A., & Sandman, C. A. (2001). When stress happens matters: Effects of earthquake timing on stress responsivity in pregnancy. *American Journal of Obstetrics and Gynecology, 184*(4), 637–642. https://doi.org/10.1067/mob.2001.111066
Goula, B. T. A., Srohourou, B., Brida, A. B., N'Zué, K. A., & Goroza, G. (2010). Determination and variability of growing seasons in Côte d'Ivoire. *International Journal of Engineering Science and Technology, 2*(11), 5993–6003.
Grace, K., Davenport, F., Hanson, H., Funk, C., & Shukla, S. (2015). Linking climate change and health outcomes: Examining the relationship between temperature, precipitation and birth weight in Africa. *Global Environmental Change, 35*, 125–137. https://doi.org/10.1016/j.gloenvcha.2015.06.010
Grace, K., Verdin, A., Dorélien, A., Davenport, F., Funk, C., & Husak, G. (2021). Exploring strategies for investigating the mechanisms linking climate and individual-level child health outcomes: An analysis of birth weight in Mali. *Demography, 58*(2), 499–526. https://doi.org/10.1215/00703370-8977484
Grépin, K. A., & Bharadwaj, P. (2015). Maternal education and child mortality in Zimbabwe. *Journal of Health Economics, 44*, 97–117.
Harari, M., & La Ferrara, E. (2018). Conflict, climate and cells: A disaggregated analysis. *Review of Economics and Statistics, 100*(4), 594.

Helgeson, J. F., Dietz, S., & Hochrainer-Stigler, S. (2013). Vulnerability to weather disasters: The choice of coping strategies in rural Uganda. *Ecology and Society, 18*(2), art2. https://doi.org/10.5751/ES-05390-180202

Hellmuth, M. E., Moorhead, A., Thomson, M. C., & Williams, J. (Eds.) (2007). *Climate risk management in Africa: Learning from practice*. International Research Institute for Climate and Society (IRI).

Hobel, C. J. (2004). Stress and preterm birth. *Clinical Obstetrics and Gynecology, 47*(4), 856–880. https://doi.org/10.1097/01.grf.0000142512.38733.8c

Hoffmann, R., & Muttarak, R. (2017). Learn from the past, prepare for the future: Impacts of education and experience on disaster preparedness in the Philippines and Thailand. *World Development, 96*, 32–51.

ICF International (2012). *Demographic and Health Survey sampling and household listing manual.* MEASURE DHS, ICF International.

Kiros, G.-E., & Hogan, D. P. (2000). The impact of famine, war, and environmental degradation on infant and early child mortality in Africa: The case of Tigrai, Ethiopia. *Genus*, *56*(3/4), 145–178. http://www.jstor.org/stable/29788659

Kiros, G.-E., & Hogan, D. P. (2001). War, famine and excess child mortality in Africa: The role of parental education. *International Journal of Epidemiology, 30*(3), 447–455. https://doi.org/10.1093/ije/30.3.447

Kudamatsu, M., Persson, T., & Strömberg, D. (2012). *Weather and infant mortality in Africa*. CEPR (Centre for Economic Policy Research) Discussion Papers 9222, C.E.P.R. Discussion Papers.

Kumar, S., Molitor, R., & Vollmer, S. (2016). Drought and Early Child Health in Rural India. *Population and Development Review, 42*(1), 53–68.

Lawton, F. G., Mason, G. C., Kelly, K., Ramsay, I. N., & Morewood, G. A. (1988). Poor maternal weight gain between 28 and 32 weeks gestation may predict small-for-gestational-age infants. *BJOG: An International Journal of Obstetrics and Gynaecology, 95*(9), 884–887. https://doi.org/10.1111/j.1471-0528.1988.tb06574.x

Lockwood, C. J. (1999). Stress-associated preterm delivery: The role of corticotropin-releasing hormone. *American Journal of Obstetrics and Gynecology, 180*(1), S264–S266. https://doi.org/10.1016/S0002-9378(99)70713-1

Lumey, L. H. (1998). Compensatory placental growth after restricted maternal nutrition in early pregnancy. *Placenta, 19*(1), 105–111. https://doi.org/10.1016/S0143-4004(98)90105-9

Lutz, W., Muttarak, R., & Striessnig, E. (2014). Universal education is key to enhance climate adaption. *Science, 346*(6213), 1061–1063.

Makate, M., & Makate, C. (2016). The causal effect of increased primary schooling on child mortality in Malawi: Universal primary education as a natural experiment. *Social Science and Medicine, 168*, 72–83.

Masih, I., Maskey, S., Mussá, F. E. F., & Trambauer, P. (2014). A review of droughts on the African continent: A geospatial and long-term perspective. *Hydrology and Earth System Sciences, 18*(9), 3635–3649.

Muttarak, R., & Pothisiri, W. (2013). The role of education on disaster preparedness: Case study of 2012 Indian Ocean earthquakes on Thailand's Andaman coast. *Ecology and Society, 18*(4), art51. https://doi.org/10.5751/ES-06101-180451

Muttarak, R., Lutz, W., & Jiang, L. (2015). What can demographers contribute to the study of vulnerability? *Vienna Yearbook of Population Research, 13*, 1–13. https://doi.org/10.1553/populationyearbook2015s001

NASA (2007). *Drought in West Africa*. https://earthobservatory.nasa.gov/images/7627/drought-in-west-africa

Painter, R. C., Roseboom, T. J., & Bleker, O. P. (2005). Prenatal exposure to the Dutch famine and disease in later life: An overview. In *Reproductive Toxicology* (Vol. 20, Issue 3, pp. 345–352). Pergamon. https://doi.org/10.1016/j.reprotox.2005.04.005

Pitt, M. M., & Sigle, W. (1998). *Seasonality, weather shocks and the timing of birth and child mortality in Senegal*. Working Paper. Providence, Rhode Island.

Riquet, C., Musiime, D., & Marita, C. (2017). National survey and segmentation of smallholder households in Côte d'Ivoire: Understanding their demand for financial, agricultural, and digital solutions (CGAP Working Paper).

Rocha, R., & Soares, R. R. (2015). Water scarcity and birth outcomes in the Brazilian semiarid. *Journal of Development Economics, 112*, 72–91. https://doi.org/10.1016/j.jdeveco.2014.10.003

Rosegrant, M. W., Cai, X., & Cline, S. A. (2002). *World water and food to 2025: Dealing with scarcity*. International Food Policy Research Institute.
Schoeps, A., Van Ewijk, R., Kynast-Wolf, G., Nebié, E., Zabré, P., Sié, A., & Gabrysch, S. (2018). Ramadan exposure in-utero and child mortality in Burkina Faso: Analysis of a population-based cohort including 41,025 children. *American Journal of Epidemiology, 187*(10), 2085–2092. https://doi.org/10.1093/aje/kwy091
Sivakumar, M. V. K., Motha, R. P., Wilhite, D. A., & Wood, D. A. (2010). Agricultural drought indices. *Proceedings of the WMO/UNISDR Expert Group Meeting on Agricultural Drought Indices*, pp. 197.
Stern, N. (2006). *The economics of climate change: The Stern review*. HM Treasury.
Strauss, R. S., & Dietz, W. H. (1999). Low maternal weight gain in the second or third trimester increases the risk for intrauterine growth retardation. *The Journal of Nutrition, 129*(5), 988–993.
Torche, F. (2011). The effect of maternal stress on birth outcomes: Exploiting a natural experiment. *Demography, 48*(4), 1473–1491. https://doi.org/10.1007/s13524-011-0054-z
UN IGME (2023). *Child mortality estimates.* https://childmortality.org
UNESCO (2015). *UNESCO science report: Towards 2030*. UNESCO.
Vicente-Serrano, S. M., Beguería, S., & López-Moreno, J. I. (2010a). A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index. *Journal of Climate, 23*(7), 1696–1718.
Vicente-Serrano, S. M., Beguería, S., López-Moreno, J. I., Angulo, M., & El Kenawy, A. (2010). A new global 0.5° gridded dataset (1901–2006) of a multiscalar drought index: Comparison with current drought index datasets based on the Palmer drought severity index. *Journal of Hydrometeorology, 11*(4), 1033–1043. https://doi.org/10.1175/2010JHM1224.1
Vicente-Serrano, S. M., Beguería, S., Gimeno, L., Eklundh, L., Giuliani, G., Weston, D., El Kenawy, A., López-Moreno, J. I., Nieto, R., Ayenew, T., Konte, D., Ardö, J., & Pegram, G. G. S. (2012). Challenges for drought mitigation in Africa: The potential use of geospatial data and drought information systems. *Applied Geography, 34*, 471–486. https://doi.org/10.1016/j.apgeog.2012.02.001
Watt, S., & Chamberlain, J. (2011). Water, climate change, and maternal and newborn health. *Current Opinion in Environmental Sustainability, 3*(6), 491–496. https://doi.org/10.1016/j.cosust.2011.10.008
Webb, P., & Reardon, T. A. (1992). Drought impact and household response in East and West Africa. *Quarterly Journal of International Agriculture, 31*(3), 230–246.
WFP (2022). *Côte d'Ivoire annual country report 2022*.
WHO (2002). *The world health report 2002: Reducing risks, promoting healthy life*. WHO.
WHO (2010). *Antiretroviral drugs for treating pregnant women and preventing HIV infection in infants.* WHO.
WMO. (1975). *Drought and agriculture*. WMO Technical Note No. 138. WMO.
WMO (2012). *Standardized Precipitation Index user guide (M. Svoboda, M. Hayes and D. Wood)*. WMO.
World Bank (2021a). *République de Côte d'Ivoire 2021–2030 - Sustaining high, inclusive, and resilient growth post COVID-19: A World Bank Group input to the 2030 development strategy*. World Bank.
World Bank (2021b). *Cote d'Ivoire*. Current climate: Climatology. https://climateknowledgeportal.worldbank.org/Country/Cote-Divoire/Climate-Data-Historical
Wu, Z. Y., Lu, G. H., Wen, L., & Lin, C. A. (2011). Reconstructing and analyzing China' s fifty-nine year (1951–2009) drought history using hydrological model simulation. *Hydrology and Earth System Sciences, 15*, 2881–2894.
Yapo, A. L. M., Diawara, A., Kouassi, B. K., Yoroba, F., Sylla, M. B., Kouadio, K., Tiémoko, D. T., Koné, D. I., Akobé, E. Y., & Yao, K. P. A. T. (2020). Projected changes in extreme precipitation intensity and dry spell length in Côte d'Ivoire under future climates. *Theoretical and Applied Climatology, 140*(3–4), 871–889. https://doi.org/10.1007/s00704-020-03124-4
Zhang, Q., Körnich, H., & Holmgren, K. (2013). How well do reanalyses represent the southern African precipitation? *Climate Dynamics, 40*(3–4), 951–962.
Zhukov, Y. M., Davenport, C., & Kostyuk, N. (2019). Introducing xSub: A new portal for cross-national data on subnational violence. *Journal of Peace Research, 56*(4), 604–614. https://doi.org/10.1177/0022343319836697

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