

## RESEARCH ARTICLE

# Impact of cash transfers on the association between prenatal exposures to high temperatures and low birthweight: Retrospective analysis from the LEAP 1000 study

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## Abstract

**Objective:** To explore the associations between prenatal temperature exposures and low birthweight (LBW) and modification by cash transfer (CT) receipt.

**Design:** Retrospective cohort study.

**Setting:** Five rural districts in Northern Ghana.

**Population or sample:** A total of 3016 infants born to women interviewed as part of the Livelihood Empowerment Against Poverty (LEAP 1000) impact evaluation between 2015 and 2017.

**Methods:** Birthweight was collected using household surveys administered to LEAP 1000 eligible women. We used a UNICEF-developed multiple imputation approach to address missingness of birthweight and applied an empirical heaping correction to the multiply imputed birthweight data. Survey data were linked to the European Centre for Medium-Range Weather Forecasts Reanalysis 5-hourly temperature averaged to weeks for 2011–2017 using community centroids. Using distributed-lag nonlinear models, we explored the lag-specific associations between weekly average temperatures greater than 30°C and LBW, and stratified by LEAP 1000 treatment.

**Main outcome measures:** Low birthweight (<2.5 kg).

**Results:** Twelve percent ( $n = 365$ ) of infants were LBW; the mean  $\pm$  SD birthweight was  $3.02 \pm 0.37$  kg. Overall, increasing temperatures were associated with increased odds of LBW, with the greatest odds observed in the 3 weeks before birth (odds ratio 1.005–1.025). These positive associations were even larger among comparison infants and null among treatment infants.

**Conclusions:** Our study found increased odds of LBW with high weekly average temperatures throughout pregnancy and the preconception period and demonstrate mitigated effects by the LEAP 1000 CT program. More evidence on the potential of CTs to serve as adaptation interventions in low- and middle-income countries is needed to protect pregnant persons and their infants from the impacts of climate change.

## KEY WORDS

cash transfers, extreme temperatures, Ghana, infants, low birthweight

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## 1 | INTRODUCTION

Low birthweight (LBW; <2500 g) is a critical metric of maternal and fetal health and a strong predictor of adverse health outcomes throughout the life course. LBW infants are at greater risk of mortality in infancy and a range of morbidities from childhood through adulthood.<sup>1</sup> More than 90% of all LBW infants are born in low- and middle-income countries (LMICs) and roughly 80% of neonatal deaths occur among LBW infants.<sup>2,3</sup> Acknowledging the public health importance of LBW prevalence reduction, the World Health Assembly set forth a global target of 30% LBW prevalence reduction by 2025.<sup>4</sup> Although there has been some observable progress towards this goal, particularly in LMICs of Southeast Asia, LBW prevalence reduction has fallen short of the World Health Assembly target and has been marginal in sub-Saharan Africa where 25% of all LBW infants are born,<sup>5</sup> suggesting a need to explore more LBW risk reduction strategies in sub-Saharan Africa.<sup>2,5</sup>

A burgeoning body of evidence suggests that prenatal exposures to temperature extremes are associated with adverse pregnancy and birth outcomes.<sup>6–14</sup> The mechanisms by which heat impacts fetal health are not yet fully understood but are hypothesised to include inflammation, oxidative stress and placental insufficiency.<sup>15,16</sup> Moreover, thermoregulatory responses of pregnant individuals may lead to dehydration and diverted blood flow and, consequently, to reduced nutrient transport to the developing fetus. However, little evidence exists on these associations in African populations,<sup>17–20</sup> where the impacts of climate change are expected to be among the most severe and where pregnant women face a ‘double-burden’ of physiological and socioeconomic vulnerability.<sup>21–24</sup> Moreover, individual- and community-level adaptation strategies in high-income contexts (i.e. air conditioning) may not be feasible or appropriate in LMICs,<sup>25</sup> highlighting a need to identify context-specific and scalable adaptation strategies in areas with limited adaptive capacity. Climate change vulnerability is a complex concept that captures socioeconomic and sociocultural factors, livelihoods and resource access, and intersectional vulnerabilities among social groups.<sup>26</sup> Hence, interventions that address the broader contributors to vulnerability while also addressing individual-level vulnerabilities have great potential to serve as adaptation strategies in the face of a changing climate.

In Africa, cash transfer (CT) programmes are common policy instruments implemented to reduce poverty and vulnerability. Impact evaluations show that CTs reduce monetary poverty, increase educational outcomes, improve health and nutrition, increase savings, investment and production, increase employment, enhance women's empowerment, and improve maternal and child health outcomes.<sup>27,28</sup> Relatedly, improved nutrition has been shown to modify the association between heat and infant health,<sup>29,30</sup> likely through mitigation of inflammatory, oxidative stress and nutrient transfer pathways. Hence, through nutritional improvements, alterations in time-use patterns, improved health-care access and other channels, CTs have great potential as

practical adaptation strategies for pregnant women and infants in the face of increasing temperatures in Africa.<sup>31</sup>

However, literature on the modification of temperature extremes on LBW by CTs in Africa is non-existent. In a related study, Ongudi and Thiam examined whether the Hunger Safety Net Programme in Kenya buffered the effects of prenatal and early life drought exposures on child malnutrition (i.e. wasting and stunting), but found no modification by programme participation status for in utero exposures.<sup>32</sup> This study aims to bridge gaps in evidence in the following ways: (1) to examine the association between temperature exposures before delivery and LBW and (2) to explore the modification of these associations by participation status in a CT targeted to pregnant women in rural Ghana. Findings from this study contribute to the limited body of evidence on the impacts of increasing temperatures on LBW and feasible strategies for temperature adaptation of pregnant women and their infants in Africa.

## 2 | METHODS

### 2.1 | Study sample

This study sample includes infants born to women interviewed as part of the Livelihood Empowerment Against Poverty (LEAP) 1000 impact evaluation conducted between 2015 and 2017. Sample selection and impact evaluation approach details can be found elsewhere.<sup>33–35</sup> In short, LEAP 1000 was a pilot unconditional CT combined with fee waivers for enrolment into the National Health Insurance Scheme targeted to pregnant and lactating women living in rural households in ten districts of Northern and Upper East regions in Ghana. The primary objective of LEAP 1000 was to reduce stunting among children in the first 1000 days of life.

An impact evaluation was conducted in five districts (Bongo, East Mamprusi, Garu-Tempane, Karaga and Yendi) to assess the effectiveness of LEAP 1000 to achieve its primary objective and assess impacts on myriad secondary outcomes. Pilot districts were selected based on poverty and malnutrition prevalence. Communities within these districts were selected based on district-level poverty rankings. Households were encouraged to apply through promotional campaigns. Pregnant and lactating women (with infants younger than 12 months) were eligible if they could provide documentation of pregnancy or a birth card from a health facility. Eligible women were then administered a proxy means test (PMT) that assessed household wealth.

A government agency (the Department of Social Welfare, not involved in the impact evaluation) chose a threshold along the sorted distribution of PMT scores that allowed for 6000 households to fall below the selected cutoff (to receive LEAP 1000). For the impact evaluation, this threshold was then exploited in a regression discontinuity design-inspired sampling strategy that assigned households falling immediately above the threshold as comparison households and

those falling immediately below (i.e. with fewer assets) to receive LEAP 1000 benefits. The LEAP 1000 impact evaluation included a sample of 1262 LEAP 1000 and 1235 comparison households interviewed at baseline (2015; pre-intervention). At endline (2017; post-intervention), 2331 households (1185 LEAP 1000 and 1146 comparison) were re-interviewed (94% follow up). Household surveys were administered to LEAP 1000 eligible women (one per household) or to household heads by trained enumerators using Computer-Assisted Personal Interviewing software.

## 2.2 | Data

### 2.2.1 | LEAP 1000 household questionnaires

At baseline, LEAP 1000 women were asked about any live-born infants aged 0–36 months in the household and, at endline, infants born since baseline. Birthweight (in kilograms) was reported by the mother based on recall or recorded on a health card from a health facility. Gestational age was not recorded on health cards nor was it collected as part of the questionnaires administered to households. We included a range of covariates in this study collected from the LEAP 1000 impact evaluation household questionnaires. These included infant sex, birth in a health facility, parity, year of birth and PMT score. Rainy season births were defined as those that occurred between April and October. Health facility births included deliveries reported to occur in a hospital, health facility, village health post or dispensary/pharmacy.

### 2.2.2 | Meteorological variables

Hourly temperature (in Kelvin) data for 2012–2017 were downloaded from the European Centre for Medium-Range Weather Forecasts Reanalysis v5 (ERA5) Land data set.<sup>36</sup> ERA5 Land is a reanalysis data set with hourly measures of land variables from 1940 to present at a  $0.25^\circ \times 0.25^\circ$  spatial resolution. Weekly averages of 2-m (vertical column) temperature (in Celsius) were calculated for all weeks (lags) in the 52 weeks preceding birth for each infant. Lags were calculated as the number of weeks before the week of delivery (i.e., lag 0 corresponds to the week of delivery and lag 52 corresponds to 52 weeks (or one year) before delivery).

## 2.3 | Statistical analysis

The primary exposure of interest in this study was weekly average temperatures in the 52 weeks before birth and our primary outcome was LBW (<2.5 kg). Fifty percent of our infant sample did not have birthweight information and 91% of the missing birthweights were accounted for by infants delivered at home (40% of women in this sample). We assumed a missing at random mechanism to impute birthweight values using a multiple imputation approach

developed by UNICEF.<sup>2</sup> We calculated Pearson correlation coefficients between an indicator for missing birthweight and a range of household-, maternal- and infant-level variables to determine auxiliary variables to include in the imputation in addition to those from the estimation model. To test the assumptions of a missing at random mechanism, we ran bivariate comparisons of sample characteristics based on birthweight missingness. We applied multiple imputation using chained equations to impute birthweight using LEAP 1000 treatment status, household size, female-headed household, number of children in the household, PMT score, district, birth size, birth in a health facility, and infant sex as auxiliary variables with five iterations, in line with previous literature.<sup>2</sup> To address the problem of heaping (rounding of birthweight values to 100-g or 500-g intervals), we randomly assigned 25% of all infants with weight equal to 2.5 kg to LBW.<sup>37</sup> We present frequencies (means  $\pm$  SD or absolute counts with percentages) of household-, maternal-, and infant-level characteristics overall and by LBW status. Differences in these characteristics across LBW status were tested using two-sample *t*-tests and  $\chi^2$  tests for continuous and dichotomous variables, respectively.

We ran a restricted distributed-lag nonlinear models (DLNM) analysis on a sub-sample of infants born after October 2016 to evaluate the 12-month period of temperature exposures after programme implementation (CTs began in September 2015). We estimated the associations between weekly average temperature exposures before birth and LBW using a DLNM.<sup>38</sup> Using a generalised linear model, we estimated the association between weekly average temperatures greater than 30°C (75th percentile) in reference to 28°C (median) and LBW adjusted for a natural spline of measurement week with three degrees of freedom (df), year of birth, birth in a health facility, parity, infant sex, PMT score and district of residence. In line with other studies,<sup>39,40</sup> we compared the Akaike information criterion of generalised linear model with different specifications of splines and df (1–6) on the exposure-response and lag-response functions and to a linear exposure-response function, and chose the specification with the lowest Akaike information criterion (basis spline functions with 6 df for the exposure-response function and 5 df for the lag-response function). To explore the potential effect measure modification of LEAP 1000 in these temperature–LBW associations, we ran stratified DLNM models by LEAP 1000 treatment status.

## 2.4 | Sensitivity analyses

To test the assumptions of our imputation method, we estimated the association between high temperature exposures during the 52 weeks before birth and birthweight among the sub-sample of infants with complete information on birthweight using generalised linear models with identity link and Gaussian family specifications, adjusted for parity, infant sex, PMT score, year of birth and district of residence. We calculated the average temperature exposure across all

52 weeks and created a binary variable if temperatures exceeded 29°C (the 75th percentile). We estimated change in birthweight (grams) in association with exposures to high temperatures in pregnancy for the overall sample of infants born after October 2016, and stratified by LEAP 1000 treatment. An interaction term was included in the pooled model to assess effect modification by LEAP 1000 treatment status.

ArcGIS was used to link the geocoded LEAP 1000 community centroids to the ERA5 grid values. Statistical analyses were conducted in Stata 16.<sup>41</sup> DLNM (*dlnm* package) and sensitivity analyses were conducted in R version 4.0.4.<sup>41,42</sup> We considered findings to be statistically significant at  $p < 0.05$  for bivariate analyses and, for DLNM, if the 95% CI did not capture the null value (odds ratio = 1).

### 3 | RESULTS

This study includes a sample of 3016 infants with complete information on birthweight (after imputation), maternal

parity, household head characteristics, antenatal care, birth month and district of residence. The selection of health facility as an auxiliary variable in the imputation in addition to the variables in the estimation model was based on its high correlation with birthweight missingness ( $r = -0.66$ ; Table S1) and that 91% of all missing birthweights occurred among infants born at home. We ruled out a missing completely at random mechanism because the sample with complete birthweight was systematically different from those infants missing birthweight (Table S2). Given that low healthcare utilisation and high socioeconomic disadvantage are characteristic of the women living in these rural regions, and the general agreement of the sample characteristics below to other studies in the area, we consider the missing at random assumption to hold.

In Table 1, we present frequency measures of household-, maternal-, and infant-level characteristics overall and by infant LBW status. Average birthweight  $\pm$  SD was  $3.02 \pm 0.37$  kg and LBW prevalence was 12% ( $n = 365$ ) in this sample of infants. LBW infants were less likely to be singletons and

**TABLE 1** Descriptive statistics of household-, maternal-, and infant-level characteristics, by LBW status ( $n = 3016$ ).

	Mean $\pm$ SD or N (%)			<i>p</i> value
	Overall sample	LBW		
		No	Yes	
<b>Household</b>				
Improved source of water	1830 (61)	1604 (61)	226 (62)	0.605
<b>Maternal</b>				
Parity (total number of live births; $n = 2980$ )	3.96 $\pm$ 2.07	4 $\pm$ 2.07	3.64 $\pm$ 2.01	<b>0.002</b>
First month of ANC	3.03 $\pm$ 1.34	3.05 $\pm$ 1.35	2.95 $\pm$ 1.26	0.176
Number of ANC visits	5.54 $\pm$ 1.88	5.52 $\pm$ 1.81	5.69 $\pm$ 1.88	0.071
<b>Infant</b>				
Singleton	2934 (97)	2601 (98)	333 (91)	<b>&lt;0.001</b>
Birthweight recorded on a health card ( $n = 2945$ )	1553 (96)	1385 (96)	168 (94)	0.111
Female	1503 (50)	1283 (48)	220 (60)	<b>&lt;0.001</b>
Born in a health facility	1929 (64)	1672 (63)	257 (70)	<b>0.006</b>
Born in the rainy season	1927 (64)	1698 (64)	229 (63)	0.625
Birthweight (kg)	3.02 $\pm$ 0.37	3.09 $\pm$ 0.32	2.47 $\pm$ 0.26	<b>&lt;0.001</b>
<b>District</b>				
Bongo	471 (16)	412 (16)	59 (16)	0.759
East Mamprusi	1142 (38)	992 (37)	150 (41)	0.175
Garu-Tempene	463 (15)	414 (16)	49 (13)	0.276
Karaga	440 (15)	371 (14)	69 (19)	<b>0.013</b>
Yendi	500 (17)	462 (17)	38 (10)	<b>0.001</b>
<b>Temperature</b>				
Weekly average temperature (°C)	28.8 $\pm$ 0.4	28.8 $\pm$ 0.41	28.8 $\pm$ 0.4	0.425
<i>n</i>	3016	2651 (88)	365 (12)	

*Note:* Improved source of water defined as the main source of drinking water or water used for cooking in the household from piped water (piped into dwelling, piped into compound yard or plot, piped to neighbour, public tap/standpipe, tube well/borehole); protected dug well; or protected spring. Rainy season births are defined as those that occurred between April and October. Health facility births included deliveries in a hospital, health facility, village health post, or dispensary/pharmacy. Boldface indicates statistical significance at  $p$  value  $< 10\%$ .

Abbreviations: ANC, antenatal care; LBW, low birthweight; SD, standard deviation.

to live in Yendi and more likely to be born in a health facility and live in Karaga compared with non-LBW infants. Average parity was  $4 \pm 2.07$  live births among the sample of non-LBW infants and  $3.64 \pm 2.01$  live births among LBW infants ( $p=0.002$ ; Table 1). Average temperatures in this region vary over the course of the year (Figure 1) and vary by district (Table S3).

### 3.1 | DLNM results

Our main DLNM analyses were conducted among the sub-sample of infants born after October 2016 to ensure that we captured the relevant exposure period that occurred after LEAP 1000 implementation (September 2015). Among the sub-sample of infants born after October 2016 ( $n=699$ ), weekly average temperatures exceeding  $30^{\circ}\text{C}$  were associated with increased odds of LBW for lags 2–14 and 35–44 (Figure 2). Among comparison infants born after October 2016 ( $n=269$ ; Figure 3A), weekly average temperatures greater than  $30^{\circ}\text{C}$  were associated with increased odds of LBW at lags 0–23 and 30–51 but these associations were

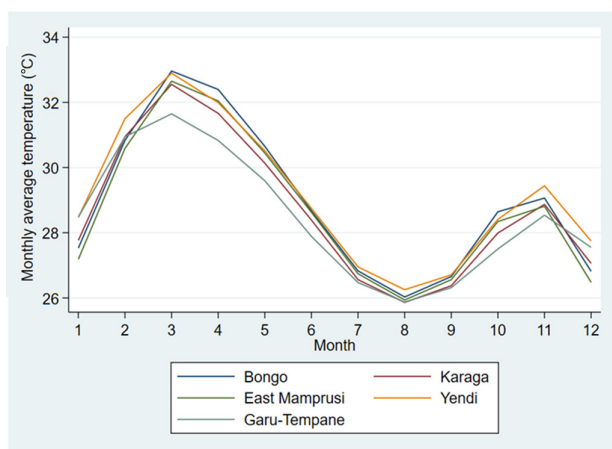


FIGURE 1 Monthly average temperatures by district in Northern Ghana; 2015–2017.

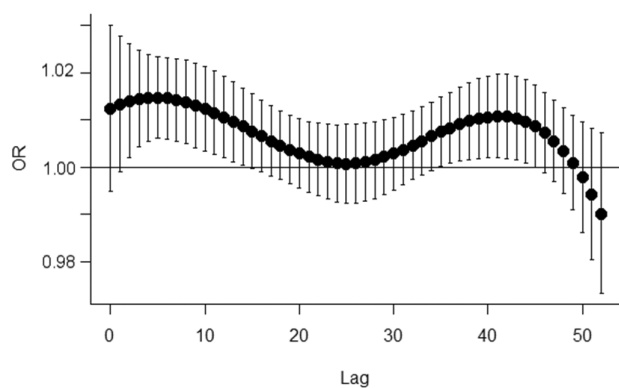


FIGURE 2 Lag-specific effects of weekly average temperatures and odds of low birthweight (LBW) in the 52 weeks before birth among the sub-sample of infants born after October 2016 ( $n=699$ ).

null among the LEAP 1000 infants ( $n=430$ ; Figure 3B), with lower odds of LBW at lags 19–24 and 49–52.

### 3.2 | Sensitivity analyses

There were 162 infants (70 comparison, 92 LEAP 1000) with complete information on birthweight, maternal parity, household head characteristics, antenatal care, birth month and district of residence born after October 2016 in this sub-sample. Among this sub-sample of infants, LBW prevalence was 4%. Table 2 presents the results of the pooled and LEAP 1000 treatment-stratified generalised linear models. Average temperatures in pregnancy exceeding  $29^{\circ}\text{C}$  were associated with lower average birthweight among the pooled ( $-136\text{g}$ ), LEAP 1000 ( $-97$ ) and comparison ( $-182$ ) samples, though these associations did not reach statistical significance. There was no evidence of effect modification of the association between high temperatures in pregnancy and birthweight by LEAP 1000 status ( $p$ -interaction = 0.216).

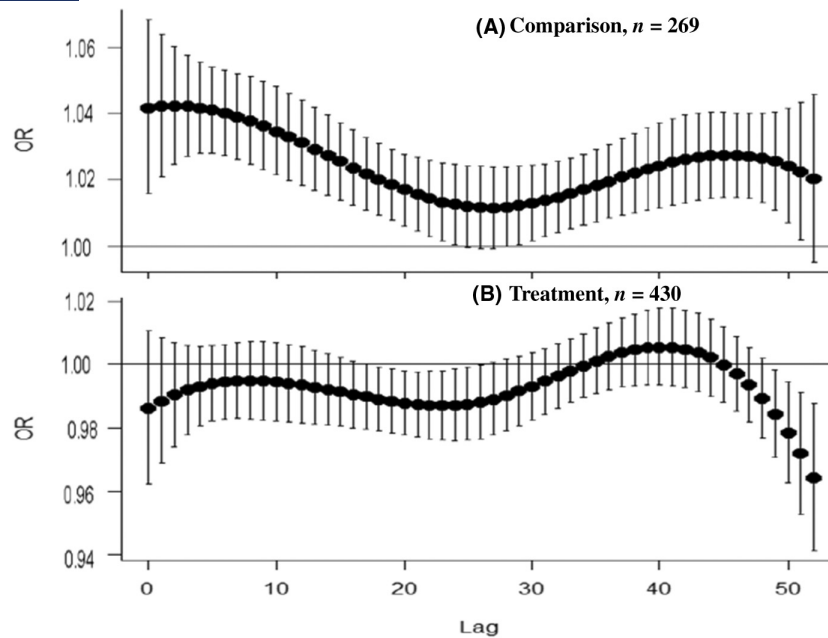
## 4 | DISCUSSION

### 4.1 | Main findings

This retrospective study used data from the LEAP 1000 impact evaluation conducted among a sample of pregnant and lactating women living in poor rural communities in rural Northern Ghana to examine the associations between weekly averaged temperatures and LBW and whether LEAP 1000 treatment protected infants from the adverse impacts of ambient temperature exposures. Using DLNM, we observed increased odds of LBW at temperatures greater than  $30^{\circ}\text{C}$  among comparison infants that were attenuated among infants born to women receiving LEAP 1000 CTs. Sensitivity analyses among a complete case sample also suggested that the LEAP 1000 infants were less affected by heat exposures than infants in the comparison group.

### 4.2 | Interpretation

Few studies on the association between ambient temperature exposures and birthweight exist in Africa with conflicting findings and none to date have examined the potential of a CT to mitigate these associations. Differences in operationalisation of temperature exposures and methodological approaches preclude precise comparisons between these findings and our study results, although we observe agreement in findings between our study and others. Using data from 19 African countries, Grace et al. found that an increased number of days above  $100^{\circ}\text{F}$  ( $37.8^{\circ}\text{C}$ ) was associated with significantly increased LBW in the first and second trimesters, but not the third trimester.<sup>17</sup> Although our study found the greatest associations in late gestation, we also observed elevated odds of LBW



**FIGURE 3** Lag specific-associations of weekly average temperatures exceeding 30°C in the 52 weeks preceding birth (referent 28°C) and odds of low birthweight (LBW) among (A) comparison ( $n = 269$ ) and (B) LEAP 1000 treatment infants ( $n = 430$ ) born after October 2016.

**TABLE 2** Adjusted associations between exposure to high temperatures during the 52 weeks before birth and change in birthweight (grams); 162 infants born after October 2016 with reported birthweight.

	Number of infants	Adjusted <sup>a</sup> change in birthweight (SE) with exposure to high temperatures (>29°C)	<i>p</i> -interaction
Pooled	162	-136 (94)	
LEAP 1000 treatment	92	-97 (132)	0.216
Comparison	70	-182 (147)	

<sup>a</sup>Models were adjusted for parity, infant sex, proxy means test score, year of birth and district of residence.

in the lag periods that would correspond to the late first/early second trimesters. Moreover, an additional month of exposure to average temperatures of 35°C was associated with a decrease in birthweight among infants born to food croppers in Kenya,<sup>43</sup> which is consistent with our findings. A recent study observed a J-shaped curve between temperature variability, which may reflect exposures to temperature extremes, and LBW risk in 37 African countries.<sup>30</sup> MacVicar et al. conducted a similar study in Uganda and found that increased temperatures throughout pregnancy were associated with increased birthweight, driven largely by exposures in the third trimester.<sup>18</sup> Discrepancies between our study findings and those of MacVicar et al. may be a result of the coarser spatial resolution of temperature data, assessment of the change in average temperatures over trimesters and the entire pregnancy, and the lack of consideration of exposures in different periods of pregnancy. Additionally, the results of our study are in accordance with studies in other settings, including those that use DLNM. Exposure to increased temperatures in later gestation were associated with reduced birthweight

or increased LBW in the USA and France.<sup>8,40,44-49</sup> Other studies, however, found no association between temperature and LBW in any window of exposure.<sup>39,50</sup>

Our main findings and sensitivity analyses suggest effect measure modification by LEAP 1000 status. Those who live in poverty with minimal access to resources and infrastructure are considered among the most vulnerable to the impacts of climate change.<sup>51</sup> Hence, poverty alleviation programmes are promising avenues to increase population-level resilience through reductions in vulnerabilities.<sup>52</sup> CTs effectively address key social determinants of health,<sup>53</sup> enabling families to be proactive against the direct and indirect effects of heat stress on health.<sup>54</sup> CTs have been shown to improve food security, nutrition, and dietary diversity, enhance women's empowerment, and increase use of healthcare services, including delivery in health facilities.<sup>55,56</sup> These improvements in maternal health transfer to the health of infants and children. More specifically, LEAP 1000 increased household consumption, improved food security, increased spending on agricultural outputs and increased the likelihood of taking out loans for productive investments.<sup>34</sup> The

improved food security may directly translate to improved nutrition, which has been shown to modify the effects of increasing temperatures on fetal growth.<sup>29</sup> On the other hand, increased agricultural inputs may buffer against the indirect impacts of heat on health through diminished agricultural outputs. There is limited, but growing, research examining the protective impacts of CT programmes on the associations between environmental exposures and infant health. Ongudi and Thiam found the effect of cumulative drought on height-for-age *z* scores to be attenuated by Kenya's Hunger Safety Net Programme among the treatment compared with the control group, though this was not observed for in utero drought exposures.<sup>32</sup> And, in support of these study findings, we have previously shown the impacts of LEAP 1000 to be modified by season of birth, such that infants born in the dry season had significantly lower odds of LBW and higher birthweight than those born in the rainy season.<sup>57</sup>

### 4.3 | Mechanisms

Pregnant women in LMICs are disproportionately exposed to extreme heat with limited opportunities to cool. Redirection of flow to the skin, away from the fetus and vital organs, may lead to inadequate nutrition or trigger acute inflammation, thus increasing LBW risk.<sup>58,59</sup> Dehydration arises when perspiration occurs without proper replacement of fluids, triggering a cascade of systemic responses in the cardiovascular and renal systems that may lead to adverse pregnancy and birth outcomes.<sup>60,61</sup> Exposure to extreme heat may trigger heat-shock protein production, which has been linked to preterm birth, an antecedent to LBW.<sup>62</sup> Inflammation is also likely to serve as a mechanism by which temperature extremes induce LBW, though its specific role remains unclear.<sup>15</sup> While oxidative stress is a natural part of gestation,<sup>63,64</sup> there is evidence from animal studies to suggest that heat stress may trigger a tip in the redox balance that starts a cascade of metabolic and physiological antecedents to LBW.<sup>16</sup> Furthermore, hormonal intermediates may play a role in heat's impacts on maternal and fetal health.<sup>65,66</sup> Hence, structural interventions that provide potable water, improved nutrition, reduce work burdens, and enhance healthcare utilisation are critical to combat the adverse health effects of extreme heat exposures.

### 4.4 | Strengths

This is the first study conducted in Africa to assess the potential of CTs to mitigate the effects of heat on LBW, thus providing some empirical basis to the role that CTs may serve in heat adaptation. This study contributes to the dearth of evidence of ambient temperature impacts on LBW in West Africa, a region that is highly vulnerable to the effects of climate change.<sup>23</sup> We conducted this study among a particularly vulnerable sample of rural pregnant women who have little to no access to cooling technologies and who spend

a large amount of time outdoors, including in subsistence farming activities. We overcome the methodological shortcomings of previous studies conducted in Africa by using DLNM to account for correlations in weekly averaged temperature exposures – a finer temporal resolution than previous studies conducted in the region. Our applied imputation approach allowed for a larger analytic sample size and our heaping correction addressed the potential outcome misclassification that is present in other studies. Although humidity is commonly controlled for in heat-health analyses, we opted to avoid such adjustments in our models to avoid dampening of the total effect of heat on LBW.<sup>67</sup> Furthermore, we ran sensitivity analyses to test our assumptions, contributing to the rigour of this study.

### 4.5 | Limitations

The following limitations were identified. In the absence of gestational age data, we assumed for our main analysis that all infants were full-term, which is not likely to hold, potentially indicating sensitive windows of exposure for infants not at risk/not exposed. However, a sensitivity analysis conducted among a sub-sample of term and ultrasound-measured infants in the MacVicar et al. study showed comparable results to their overall results, confirming our findings despite the absence of gestational age to contextualise LBW.<sup>18</sup> The assumption of our imputation approach was a missing at random mechanism, with birthweight missingness largely explained by birth outside a health facility; however, this does not preclude the possibility that some infants' birthweights are missing not at random because lower birthweight infants are less likely to be weighed immediately, if at all, to prioritise acute care. Additionally, birth outside a health facility accounted for 91% of birthweight missingness, so the remaining 9% may not be represented by this assumed mechanism. Imputing such a large proportion of an outcome variable has been considered valid,<sup>68,69</sup> work by Madley-Dowd et al. suggests that complete auxiliary variables can be used as valid approaches to impute outcomes with a high degree of missingness.<sup>70</sup> We conducted sensitivity analyses among a complete case sample to test our missingness assumptions, but the results should be interpreted with caution because of small sample sizes. The specification of basis functions in DLNMs is still a growing area and the optimal choices for defining functions are often not straightforward.<sup>71</sup> There is a potential for exposure misclassification given the rather coarse spatial resolution of the temperature data and the aggregation of household-level geolocations to community-level centroids, though we do not consider this to be a major concern given the narrow temperature variability in this region and the predominant outdoor livelihoods of this population. Live-birth selection is a looming concern in studies that assess prenatal exposures and outcomes at birth and a recent study suggests that this bias, in certain circumstances, may attenuate these associations.<sup>72,73</sup> Residual confounding and uncontrolled confounding may

be problematic as clinical information relevant to LBW was not collected in the LEAP 1000 household surveys. Further, we did not adjust for precipitation, other modes of daily activities, air pollution, or malaria risk, which may lead to inflated results. External validity is limited as this study was conducted among a sample of pregnant women residing in impoverished communities in rural Ghana, so we caution any generalisations.

## 5 | CONCLUSIONS

Our study contributes to the limited literature on not only the associations between ambient temperatures and LBW in LMICs, but also the potential for CT programmes to mitigate these impacts. Future research should address the paucity of population-level clinical information on fetal health from LMICs. Detailed and accurate measures of environmental exposures, such as biomarkers or individual monitoring, would move this field forward. Furthermore, continued evaluations of social, nutritional, physiological, or epigenetic strategies to promote individual- or community-level heat adaptation are of immense value in this time of impending climate change.

### AUTHOR CONTRIBUTIONS

Sarah LaPointe, Tia Palermo, and Ana Bonell designed the study. Tia Palermo and Clement Adamba were involved in data collection for LEAP 1000. Sarah LaPointe, Shao Lin, and Ana Bonell were involved in data analysis. Sarah LaPointe and Ana Bonell drafted the manuscript. All authors reviewed and approved the final manuscript.

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### CONFLICT OF INTEREST STATEMENT

None declared.

### DATA AVAILABILITY STATEMENT

The LEAP 1000 impact evaluation data are publicly available at [https://data.cpc.unc.edu/projects/13/view#res\\_226](https://data.cpc.unc.edu/projects/13/view#res_226). The European Centre for Medium-Range Weather Forecasts ERA5 data are publicly available at <https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview>.

### ETHICS APPROVAL

The LEAP 1000 evaluation study was reviewed by the Ethics Committee for the Humanities of the University of Ghana.

The evaluation is registered in the International Initiative for Impact Evaluation's (3ie) Registry for International Development Impact Evaluations (RIDESTUDY-ID-55942496d53af) and in the Pan African Clinical Trial Registry (PACTR202110669615387). The current analysis uses de-identified data and was exempted from institutional review board review at the University at Buffalo. Verbal consent was ascertained by all survey respondents.

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## SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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