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Chronic Stress and Severe Water Insecurity During the Historic 2022 Drought in Northern Kenya Were Associated With Inflammation Among Daasanach Seminomadic Pastoralists

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ABSTRACT

Objective: Extreme climatic events, like droughts, are increasing in frequency and severity. Droughts disrupt community livelihoods and resources with serious implications for human biology. This study investigated how chronic stress, measured by fingernail cortisol concentration (FCC), and water insecurity status were predictive of C-reactive protein (CRP), a biomarker of inflammation, during a historic drought among Daasanach seminomadic pastoralists.

Methods: Data were collected at the height of the 2022 drought from 128 Daasanach household heads aged 16–80 years in northern Kenya using household surveys, anthropometric measurements, and dried blood spots to assess CRP levels and fingernails to assess FCC. We employed mixed-effects linear and logistic regression models to examine the relationships between log-transformed FCC, high water insecurity status measured via the Household Water Insecurity Experiences ($\text{HWISE} \geq 24$) scale, and serum-equivalent CRP (log-transformed and dichotomized at mild, low-grade inflammation ≥ 1 mg/L) adjusted for covariates.

Results: The mean serum-equivalent CRP was 4.1 mg/L and 56.3% of Daasanach adults had at least mild, low-grade inflammation. Linear models indicated that ln(FCC) was positively associated with ln(CRP) ($\beta = 0.56$, $\text{SE} = 0.12$; $p < 0.001$). Further, logistic models demonstrated that ln(FCC) ($\text{OR} = 2.69$, 95% CI: 1.84–3.95; $p < 0.001$) and high water insecurity ($\text{OR} = 2.23$, 95% CI: 1.34–3.72; $p = 0.002$) were both associated with greater odds of low-grade inflammation.

Conclusion: This study provides evidence for how chronic stress and severe water insecurity may impact inflammation levels among pastoralists during drought. Since inflammation is central to cardiometabolic disease etiology, this is an additional reason to mitigate the negative health impacts of droughts and water insecurity exacerbated by climate change.

1 | Introduction

Extreme climatic events, like droughts, are increasing in frequency and severity with anthropogenic climate change (Pörtner et al. 2023). Droughts pose a significant threat to rural communities and, in particular, pastoral communities throughout the Greater Horn of Africa (Megersa et al. 2014; Muheki et al. 2024). Droughts have long-term consequences not only for the environment and human health, but also for livelihoods, which trigger a cycle of health deterioration (WHO 2023). Extreme droughts pose a particular risk for subsistence populations like farmers, agropastoralists, and pastoralists whose livelihoods and economic systems are strongly tied to environmental conditions (Bethancourt et al. 2023; Wan et al. 2017).

Extreme drought can affect human biology and health directly and indirectly (Ebi and Bowen 2016). Direct health impacts to human biology include impaired organ, immune, and neuroendocrine function (Ebi and Bowen 2016; Rosinger 2023a). Indirect health effects can result from climate effects on the environment that pastoral communities live in and the animals they rely on for their livelihoods. Increasingly dry conditions compound the hardships already faced by pastoralist communities by decreasing water availability and quality, which can concentrate pollutants and pathogens in remaining water sources and increase the risk of infectious disease (Chang et al. 2019; Rosinger 2023a; Yang, Ma, and Yuan 2023). Drought also decreases grazing resources for livestock, leading to livestock attrition, reducing availability of nutritious food, and increasing malnutrition in these communities (Galvin 1992).

Importantly, these impacts on the environment and livestock may combine to exacerbate both stress and inflammation in the body (Apanius 1998; Dhabhar 2008). Chronic exposure to drought conditions can increase psychological stress (Straight et al. 2022), which activates the sympathetic nervous system and the hypothalamic–pituitary–adrenal (HPA) axis. The HPA axis regulates the body's stress response, leading to the release of catecholamines and glucocorticoids (Miller and O'Callaghan 2002), which suppress the immune system and, under normal physiological conditions, decrease inflammation in the body, allowing the host to harness resources to cope with short-term stressors (Miller and O'Callaghan 2002).

Systemic inflammation in the body is commonly assessed by measuring circulating C-reactive protein (CRP), an acute-phase protein produced by the liver. CRP levels typically increase in response to infections and pro-inflammatory stimuli and decrease in response to glucocorticoids and other anti-inflammatory signals (Heidari and Lawrence 2023; Ridker and Morrow 2003; Sproston and Ashworth 2018). However, chronic stress, particularly in industrialized populations, can lead to prolonged secretion of catecholamines and glucocorticoids, resulting in the dysregulation of the pathways that regulate CRP. This dysregulation can then lead to elevated levels of circulating CRP, increasing the risk of cardiovascular disease and metabolic syndrome (Avan et al. 2018; Kaptoge, Angelantonio, and Lowe 2010).

A large body of work has documented the relationship between stress and inflammation, demonstrating that increased stress can lead to chronic inflammation, but this has been conducted mostly in industrialized populations (Coussons-Read, Okun, and Nettles 2007; Johnson, Abbasi, and Master 2013; Miller and O'Callaghan 2002; Rohleder 2019). The relationship between stress and inflammation among nonindustrialized, pastoralist populations is less clear (Lukas, Campbell, and Campbell 2005). In populations exposed to prolonged stress, such as pastoralists facing drought, chronic activation of the HPA axis may lead to long-term dysregulation. Understanding the role of the HPA axis in inflammation could provide insight into how prolonged stress in pastoralist populations contributes to health disparities.

Other work has explored how drought affects stress and undernutrition by examining the relationships between these variables and long-term rainfall variability, grazing pressure, cattle mortality, and household food and water insecurity (Bethancourt et al. 2023; Megersa et al. 2014; Rosinger et al. 2024). Pastoralist populations have a long history of dealing with droughts (Anyah and Qiu 2012; Little 1989; Tierney, Ummenhofer, and Demenocal 2015; Verschuren, Laird, and Cumming 2000). Prior work has demonstrated that droughts negatively affect pastoralist health, diet, and growth (Fratkin 2013; Iannotti et al. 2022; Straight et al. 2022). Yet, how chronic stress influences pastoralists' inflammation during drought conditions remains underexplored. More work is needed to understand how droughts are embodied via increased stress and chronic inflammation, particularly among small-scale populations as most of this work has occurred in industrialized populations.

The Greater Horn of Africa, an area characterized by extreme heat and low rainfall, is particularly impacted by climate change, including both drought and flooding, with projections indicating that climate change will exacerbate existing vulnerabilities (Anyah and Qiu 2012; Muheki et al. 2024; Tierney, Ummenhofer, and Demenocal 2015). Between October 2020 and April 2023, the Greater Horn of Africa, including northern Kenya, experienced the most severe drought in 40 years. This severe drought resulted in widespread water and food shortages, created food insecurity for 51 million (5.4 million in Kenya), and caused the deaths of millions of livestock (WHO 2023). In addition to water and food insecurity, many pastoralist populations lost most of their livestock due to the drought, placing them under severe chronic stress, with no clear end in sight during the fourth failed rainy season in 2022 (Rosinger et al. 2024). The health and socioeconomic implications of this historic drought profoundly affected their livelihoods and the subsequent impact on human biology is only beginning to be understood (Rosinger et al. 2024).

In this study, we use a case study of the historic drought to explore how this prolonged period of extreme chronic stress impacts biology and inflammation in pastoralist communities. In this study, we use data from the peak of the 2022 historic drought—after approximately 1.5 years of experiencing drought conditions—to test how chronic stress, measured by fingernail cortisol concentration (FCC), and water insecurity status, measured with a validated experiential scale, are associated with inflammation levels, as measured by CRP among Daasanach seminomadic pastoralists living in northern Kenya. We hypothesized that chronic stress via elevated cortisol would result in an increased production of CRP as part of the body's inflammatory response among this pastoralist community. Thus, we predicted that both FCC and high levels of water insecurity would be positively associated with greater levels of CRP. Documenting how chronic stress and environmental factors influence inflammation can provide valuable insights into how extreme climatic events affect pastoralist health and biology.

2 | Methods

2.1 | Study Settings and Participants

Daasanach are a seminomadic pastoralist ethnic group who live in the arid and semiarid regions of northern Kenya and southwestern Ethiopia (Gebre 2012; Kiura 2005; Mwamidi et al. 2018). Approximately 19 000 Daasanach live in northern Kenya, dispersed throughout 26 villages on the northeastern shore of Lake Turkana, near the Ethiopian border (KNBS 2019). They traditionally relied on livestock, such as cattle, goats, and camels, for their livelihoods and primary food and hydration sources (Kiura 2005). Through increasing market integration, there is variation in access to market foods and food aid as well as water infrastructure throughout the 26 villages. The Daasanach Human Biology Project began a longitudinal study on long-term perspectives on water insecurity, food insecurity, nutrition, energetics, and environmental exposures in 2019 (Bethancourt et al. 2021; Rosinger et al. 2021). Seven Daasanach communities were initially selected to capture a range of exposures, including access to water sources, market integration, and the subsequent changes in lifestyles ranging from traditional seminomadic to more sedentary in the market town of Illeret—with greater details published elsewhere (Ford et al. 2023; McGrosky et al. 2024; Rosinger et al. 2024; Sadhir et al. 2024; Swanson, Bethancourt, et al. 2023; Swanson, Nzunza, et al. 2023).

The data for this paper come from the 2022 survey wave, collected in June–July of that year, after participants had endured just under 2 years of drought. During this period, they experienced extreme conditions due to inadequate rains resulting in heavy livestock losses, compounded by severe food and water shortages. At the time of data collection, it was unclear when the drought would end. Data were collected from 182 household heads (both male and female when present), all of whom provided complete anthropometric and survey data. Two adults per household were invited to participate, however, some households had an adult away traveling or only had one adult in the household because they were widowed. In those situations, we interviewed one adult. All household heads were asked to provide fingernail samples and dried blood spot (DBS) samples; however, some adults did not have sufficient nail length, and some did not bleed sufficiently for DBS collection (full methods described below in Section 2.2). This resulted in 161 participants who had fingernail samples collected and 147 who had DBS collected. Data across all parameters were available for 128 household heads (aged 16–80 years) and thus used in this analysis. Survey data were collected by local Daasanach field assistants in concert with the broader research team and were supervised in the field by the senior author on this paper (A.Y.R.).

This research was carried out in accordance with the ethical principles outlined in the Declaration of Helsinki. The study received approval from the Institutional Review Board at Pennsylvania State University (STUDY00009589) and the Kenyan Medical Research Institute (KEMRI) (KEMRI/RES/7/3/1). Additionally, authorization was obtained from the Director of Health for Marsabit County in Kenya and permission was granted from community elders in each of the study communities. Community translators provided study information to participants, who gave informed consent, both in writing and verbally, to ensure their voluntary and informed participation in the research.

2.2 | Outcome

2.2.1 | C-Reactive Protein (CRP)

CRP was measured to assess levels of systemic inflammation. DBS samples were obtained following standard protocol for field settings (McDade, Williams, and Snodgrass 2007). Finger-prick blood was applied to filter paper cards (Whatman 903 card) and allowed to dry completely at room temperature before local storage in a −20°C freezer in the field. All DBS samples were then transported with cold packs from Kenya to Penn State University and then shipped with dry ice to the Human Evolutionary Biology and Health Lab at Baylor University for −80°C storage and lab analysis. Concentration of CRP was determined using a validated and published modification (Blackwell et al. 2010; Urlacher et al. 2018) of a high-sensitivity ELISA protocol for DBS samples (McDade, Burhop, and Dohnal 2004). All samples were run in duplicate. Intra- and inter-assay CVs were 6.7% and 1.2%, respectively. Three samples read below the assay's lower limit of detection (0.05 mg/L) and were assigned a value of 0.036 mg/L (LOD/sqrt[2]). Raw CRP values were then converted to their serum-equivalent following the assay-specific equation provided in (Urlacher et al. 2018):

$$\mathrm{CRP}_{\mathrm{serum}} = e^{[1.2 \times \ln\mathrm{CRPDBS} + 0.3405]}$$

For statistical analyses, serum-equivalent CRP levels were analyzed both continuously, with data natural log-transformed, and dichotomized at ≥ 1 mg/L as the cutoff for mild, but still costly systemic inflammation. This low cutoff value of ≥ 1 mg/L to distinguish low-grade inflammation follows prior research with small-scale populations (Goosby et al. 2015; Urlacher et al. 2018) and is supported by the rare occurrence, and even absence, of chronic CRP elevation above 3 mg/L among adults in these settings (Mcdade et al. 2012).

2.3 | Primary Predictor

2.3.1 | Fingernail Cortisol Concentration

Cortisol concentration was measured from fingernail samples since we aimed to assess chronic stress, whereas, saliva, urine, and blood samples provide diurnal and day-to-day variations in cortisol (Tavares et al. 2017). Fingernails and hair provide a more stable measure of long-term cortisol levels, yet nail sample collection is preferred by Daasanach over hair samples due to cultural reasons (Firkey et al. 2023; Phillips et al. 2021). Fingernails were collected following protocol by Davison (Davison et al. 2020) with the participants' consent by clipping to the fingernail bed from at least one finger and all 10 if possible to ensure a sufficient sample quantity. The collection process involved cleaning the fingers with an alcohol swab and placing the nail samples in a clean, dry brown bag to avoid contamination. Samples were shipped at room temperature to the Biomarker Core Laboratory at Pennsylvania State University for analysis. In the laboratory, fingernail samples were washed and dried to eliminate surface contaminants. Cortisol was then extracted from the dried samples using a Salimetrics Assay Diluent and assayed in duplicate following the manufacturer's instructions, with intra- and inter-assay coefficients of variation of 10.0% and 7.6%, respectively (Voegel et al. 2018). Detailed methods of the analysis have been published elsewhere (Rosinger et al. 2024). We excluded one outlier greater than 11 standard deviations beyond the highest value in the study (Chen et al. 2023). During statistical analysis, FCC values were natural log-transformed due to the slight right-skewness of the data.

2.4 | Secondary Predictor

2.4.1 | Water Insecurity Status

Household water insecurity was assessed using the 12-item Household Water Insecurity Experiences (HWISE) scale, which has been validated in low- and middle-income countries (Young et al. 2019) and previously used at this study site (Bethancourt et al. 2023; Rosinger et al. 2024). This scale ascertains information on a range of experiences in the prior 4 weeks, such as worrying about having enough water to going to sleep thirsty. Each of the 12 questions has responses of never, rarely, sometimes, and often/always, which when summed provide a score from 0 to 36, with higher scores indicating greater water insecurity. Both adults within the household (when present) were asked these questions separately to examine individual perceptions of household water insecurity. Prior work has shown that water insecurity levels were already high among Daasanach prior to the drought (Ford et al. 2023) and these levels increased due to the drought (Rosinger et al. 2024). Therefore, for this analysis, we dichotomized HWISE scores at the cutoff of high water insecurity ≥ 24 following categorization by Frongillo and colleagues (Frongillo et al. 2024) to test how households experiencing problems with nearly every water issue compared to those with fewer or less severe water problems.

2.5 | Covariates

In the analysis, we adjusted for covariates which may influence either inflammation or the primary and secondary predictors (Lacourt et al. 2018; Phillips et al. 2021; Rohleder 2019; Tallman et al. 2022). The covariates included participants' age, sex (male/female), body mass index [BMI (kg/m^2)], history of malaria infections in the past 5 years, household income, number of moves in the previous year, livestock wealth, and weekly water fetching trips. To calculate BMI, we measured each participant's weight in kilograms (kg) using a Tanita digital scale to within 0.1 kg while wearing light clothing and barefoot. We measured participant height in centimeters (cm) using a stadiometer to the nearest 0.1 cm while they were barefoot and without head coverings and converted this value to meters (m). Acute malaria infection is associated with elevated CRP and asymptomatic malaria is associated with higher CRP compared to healthy controls (Wilairatana et al. 2021); yet, in malaria endemic regions, past malaria infections may dysregulate CRP levels and the relationship between CRP and malaria is not clear (Eriksson et al. 2013; Peto et al. 2016). During the 2022 field season, there were no current reported malaria cases in Illeret; therefore, to control for history of malaria infection, each participant was asked about whether they had a previous malaria infection during the last 5 years (yes or no). The 5-year cutoff was chosen as a practical window for capturing recent malaria episodes that could have lingering effects, while excluding the influence of more distant, less relevant infections.

To control for economic and agricultural assets of households which may mitigate stress during a drought, we adjusted for both household income and livestock wealth. Household income was assessed by asking participants to report their total earnings in the past month, measured in Kenyan shillings. Daasanach view livestock as their bank accounts, often referring to them as “four-legged wealth”; thus, we measured livestock wealth by inquiring about the number of camels, goats, sheep, donkeys, and other animals owned by the household with the number of each animals multiplied by a standardized monetary value based on market price in 2022 and then summed and natural log-transformed as described elsewhere (Rosinger et al. 2024). To assess mobility and changes in residence over the past year, we asked participants how many times they had moved from their permanent home since the previous year which can provide a helpful proxy for physical activity levels but also exposure to livestock dung. Water fetching is a coping strategy to deal with water insecurity and increase water availability in the household. We adjusted for the total number of trips made by the household to fetch water each week as an indicator of ability to access water as well as amount of physical activity given that each trip takes on average 1–2 h; we divided this variable by three as that was the most common reported number per day. As all participants in this sample were classified as severely food insecure and there was no variation in severity of food insecurity, we did not include food insecurity in analyses, though results were consistent when it was included (data not shown).

2.6 | Statistical analysis

Data cleaning and analyses were performed using Stata Version 15.1 (College Station, TX). We set statistical significance to an alpha level of 0.05 for two-tailed tests. We assessed the normality of CRP, FCC, and water insecurity data using graphical methods and found CRP was right-skewed and FCC was slightly

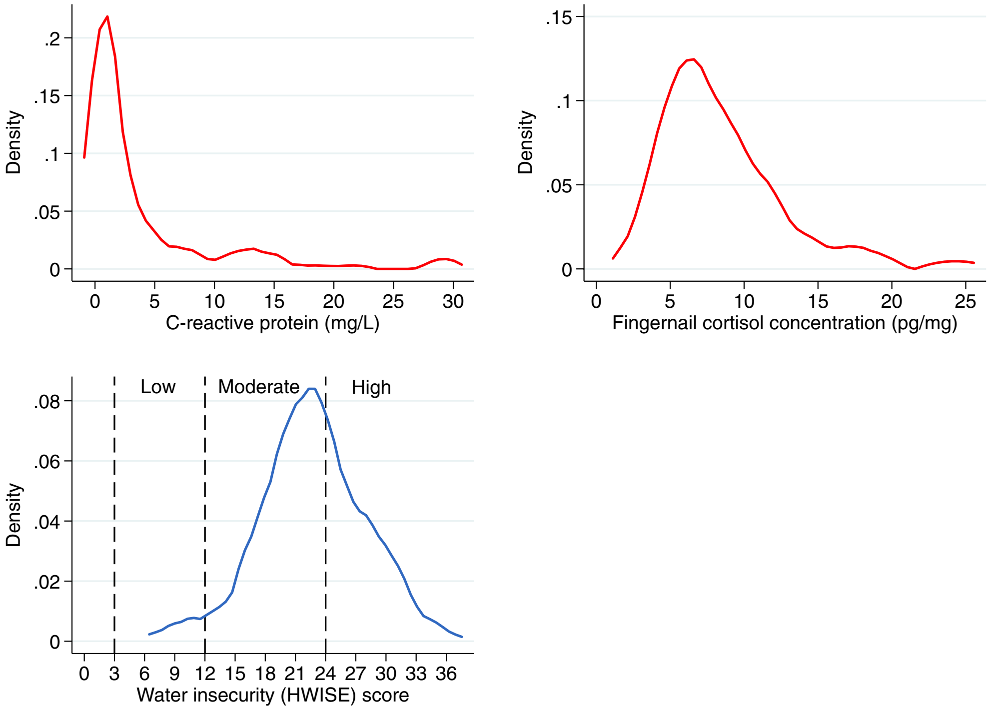

FIGURE 1 | Kernel density plot of C-reactive protein, fingernail cortisol concentration, and water insecurity during 2022 drought among 128 Daasanach adults in northern Kenya ($n = 128$). *Note:* C-reactive protein is converted to serum-equivalent. Low water insecurity (3–11), moderate water insecurity (12–23), high water insecurity (24–36).

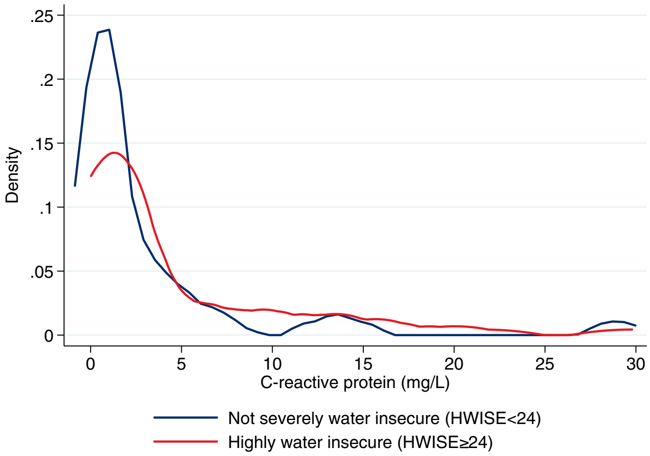

FIGURE 2 | Kernel density plot of C-reactive protein by water insecurity severity status among Daasanach adults in northern Kenya ($n = 128$). *Note:* C-reactive protein is converted to serum-equivalent. HWISE, Household Water Insecurity Experiences scale.

right-skewed (Figure 1). As a result, CRP and FCC were natural log-transformed to address the skewness; the transformed data were normally distributed. Additionally, we used kernel density plots to generate separate distribution curves for CRP by water insecurity status (Figure 2). We modeled CRP in two ways to explore the relationship between inflammation and FCC and severe water insecurity. We first used linear models to assess the full range of variation in CRP levels; second, we used a dichotomized approach with elevated CRP indicative of mild, low-grade inflammation to understand differences between individuals with no inflammation compared to those with any amount of low-grade inflammation.

We employed mixed-effects linear and logistic regression models with observations nested at the community and household levels to account for clustering in exposures and outcomes, incorporating robust standard errors. We first estimated models examining the bivariate association between log-transformed FCC and log-transformed CRP (Model 1), and subsequently between high water insecurity status and log-transformed CRP (Model 2). We then reestimated the same model with both predictors included and adjusted for all covariates (Model 3). We used the same modeling strategy to assess the relation with the odds of elevated CRP (< 1 mg/L vs. ≥ 1 mg/L). We visualized these relationships with a forest plot showing the odds of elevated CRP by these predictors and covariates. Finally, we examined the predicted probability of elevated CRP by severe water insecurity status using the margins command (Williams 2012).

To assess sensitivity of the results, we first reestimated the mixed-effects logistic regression model with a more conservative elevated CRP cutoff of ≥ 3 mg/L. Second, we excluded participants who may have been experiencing an acute, active infection by restricting analyses to those with CRP levels < 10 mg/L and reestimated the mixed-effects linear and logistic regression fully-adjusted Model 3 in the primary analyses.

3 | Results

3.1 | Descriptive Statistics

Data from 128 adult household heads collected in 2022 were analyzed, with descriptive characteristics outlined in Table 1. Participants had a mean age of 43 years (SD = 15.3), 44.5% were

TABLE 1 | Descriptive characteristics of adults in the Daasanach Human Biology Project 2022 study wave with fingernail cortisol and C-reactive protein data ($n = 128$).

Variable	Mean or percent	Standard deviation	Range (min–max)	
Age (years)	43.0	15.3	16	80
Male (%)	44.5	49.9	0	100
Weight (kg)	50.75	8.7	36.7	90.4
Height (cm)	166.8	7.5	145	186.9
BMI (kg/m^2)	18.22	2.9	13.44	37.05
C-reactive protein (CRP, serum-equivalent) (mg/L)	4.06	7.0	0.02	45.34
CRP (natural log-transformed)	0.18	1.7	−3.87	3.81
Elevated CRP (% ≥ 1 mg/L)	56.25	49.8	0	100
Fingernail cortisol concentration (FCC) (pg/mg)	8.48	4.2	2.34	24.33
FCC (natural log-transformed)	2.03	0.46	0.85	3.19
Water insecurity (HWISE score)	22.6	5.1	8	36
High water insecurity (% HWISE ≥ 24)	39.8	49.2	0	100
Previous malaria infection in last 5 years (%)	73.4	44.3	0	100
Household income (natural log-transformed)	4.69	3.7	0	9.2
Times moved in the prior year	3.4	3.9	0	15
Livestock wealth (natural log-transformed)	9.4	3.6	0	12.8
Weekly water fetching trips (per 3)	5.3	1.4	0	9.3

Abbreviation: HWISE, Household Water Insecurity Experiences scale.

male, and had a mean BMI of 18.2 kg/m^2. The mean FCC was 8.48 pg/mg (range: 2.34–24.33; SD = 4.23) (Table 1). The mean HWISE score was 22.7; no participants experienced no-to-marginal water insecurity (scores 0–2), only 3.1% experienced low water insecurity (scores 3–11), 57% experienced moderate water insecurity (scores 12–23), and ~40% of participants experienced high water insecurity levels (scores ≥ 24) (Figure 1). Further, > 90% of participants experienced each of the 12 HWISE items at least once in the prior month and > 55% of participants experienced each of the items three or more times. The distribution of CRP values varied significantly by whether adults experienced severe water insecurity or not (Figure 2). In the sample, mean serum-equivalent CRP was 4.06 mg/L (range: 0.02–45.34; SD = 7.0), with 56.3% of participants exhibiting elevated (≥ 1 mg/L) levels. Participants for whom we had CRP and FCC data did not significantly differ from those who had either missing CRP or FCC data ($n = 54$) in age (mean = 39 years; SD = 17), sex (37.7% male), BMI (mean = 18.1; SD = 3.0), and water insecurity score (mean = 22.7; 43.4% high water insecurity) (data not shown).

3.2 | Linear Models

The unadjusted linear regression model revealed each unit increase in ln(FCC) was associated with an increase of 0.58 ln(CRP) ($\beta = 0.58$, SE = 0.11; $p < 0.001$) (Table 2, Model 1). Individuals experiencing severe water insecurity had slightly higher ln(CRP) levels ($\beta = 0.32$, SE = 0.22; $p = 0.15$) compared to those not experiencing high levels of water insecurity, but this association was not statistically significant (Table 2, Model 2). When both predictors and all covariates were included in the same model, the effect size for FCC was consistent with the bivariate analysis ($\beta = 0.56$, SE = 0.12; $p < 0.001$), and the effect of severe water insecurity remained nonsignificant ($\beta = 0.23$, SE = 0.19, $p = 0.22$; Table 2, Model 3).

Among covariates, prior malaria infection in the last 5 years was associated with higher CRP levels ($\beta = 0.63$, SE = 0.13; $p < 0.001$). In contrast, the number of times moved in the prior year ($\beta = -0.09$, SE = 0.04; $p = 0.009$) and the frequency of water fetching trips per week ($\beta = -0.26$, SE = 0.09; $p = 0.005$) were both protective, associated with lower inflammation (Table 2, Model 3).

3.3 | Logistic Regression

The bivariate logistic regression models indicated that both ln(FCC) and high water insecurity levels were independently associated with higher odds of elevated CRP (Table 3, Models 1 and 2). After full adjustment for covariates and including both main predictors, each unit increase in ln(FCC) was associated with a greater than two-fold increase in the odds of elevated CRP levels (OR = 2.69, 95% CI: 1.84–3.95; $p < 0.001$). Moreover, experiencing high levels of water insecurity was associated with 123% higher odds of elevated CRP (OR = 2.23, 95% CI: 1.34–3.72; $p = 0.002$) compared to those not experiencing severe water insecurity (Table 3, Model 3; Figure 3).

Among the control variables, each additional move in the prior year was associated with 7.5% lower odds of elevated CRP, which approached significance (OR = 0.93; 95% CI: 0.85–1.00; $p = 0.06$). Further, each three trips fetching water per week was associated with a 29% lower odds of elevated CRP levels (OR = 0.71: 95% CI: 0.59–0.85; $p < 0.001$) (Table 3, Model 3; Figure 3).

TABLE 2 | Mixed-effects linear regression model testing association of fingernail cortisol concentration and severe water insecurity on natural log-transformed C-reactive protein ($n = 128$).

VARIABLES	**Model 1** ln(CRP) Beta (SE)	**Model 2** ln(CRP) Beta (SE)	**Model 3** ln(CRP) Beta (SE)
Fingernail cortisol concentration (ln)	0.58***		0.56***
	(0.11)		(0.12)
High water insecurity (% HWISE ≥ 24)		0.32	0.23
		(0.22)	(0.19)
Previous malaria infection in last 5 years			0.63***
			(0.16)
Household income (ln)			−0.03
			(0.03)
Number of times moved in last year			−0.09***
			(0.04)
Livestock wealth (ln)			−0.02
			(0.04)
Weekly water fetching trips (per 3)			−0.26***
			(0.09)
Individual's age (years)			0.00
			(0.01)
Male (vs. female)			0.06
			(0.49)
BMI (kg/m^2)			0.04
			(0.04)
Observations	128	128	128

Note: Mixed effect models with observations nested within seven communities and 99 households with robust standard errors. CRP is serum-equivalent.
Abbreviations: HWISE, Household Water Insecurity Experiences scale; Ln, natural log-transformed.
***$p < 0.01$, **$p < 0.05$.

Using the fully-adjusted logistic regression model (Table 3, Model 3), we estimated the predicted probability of elevated CRP by water insecurity status. Experiencing high levels of water insecurity was associated with a 17.2 percentage point increase in the predicted probability of elevated CRP. Specifically, individuals experiencing high levels of water insecurity had a 66.6% (95% CI: 60.5–72.7) predicted probability of having elevated CRP, whereas 49.4% (95% CI: 39.8–58.9) of those without high water insecurity had elevated CRP (Figure 4).

3.4 | Sensitivity Analysis

When CRP was dichotomized at ≥ 3 mg/L rather than ≥ 1 mg/L, 31.3% of adults were classified as having elevated CRP. Results of the reestimated mixed-effects logistic regression model were consistent in the association between FCC and elevated CRP (OR = 2.78; 95% CI: 1.10–7.02; $p = 0.032$), but high WI, while still in the same direction was no longer significantly associated with elevated CRP (OR = 1.32; 95% CI: 0.43–4.11) (Table S1, Model 3).

Restricting the sample to those with CRP < 10 mg/L excluded 16 participants. Results for the continuous mixed-effects linear regression were attenuated as ln(FCC) was no longer significant with ln(CRP) and water insecurity status remained nonsignificant (Table S2, Model 3a). In contrast, results for the mixed-effects logistic regression were consistent with the primary results as effect sizes (ORs of 2.3 and 1.95) and significance remained large for both primary and secondary predictors (both $p < 0.001$) (Table S2, Model 3b).

4 | Discussion

This paper aimed to understand how chronic stress and water insecurity severity were associated with inflammation among Daasanach seminomadic pastoralists during the historic 2022 drought in northern Kenya. Overall, we found that greater fingernail cortisol concentration was associated with both greater CRP levels and odds of mildly elevated CRP, with each unit increase in ln(FCC) associated with nearly 2.7 times the odds of serum-equivalent CRP ≥ 1 mg/L. Further, we found that Daasanach who experienced high levels of water insecurity, while not associated with continuous ln(CRP), had 2.2 times the odds of CRP ≥ 1 mg/L than those with fewer water problems. These results underscore how the multifaceted nature of stress experienced during extreme droughts and environmental factors may shape inflammatory responses among seminomadic pastoralists.

4.1 | Chronic Stress and Inflammation

This study found that FCC was positively associated with CRP levels and odds of mildly elevated CRP, indicating that greater chronic stress is associated with increased inflammation among pastoralists during a severe drought. Fingernail cortisol serves as a retrospective indicator of average cortisol levels from 3 to 5 months prior to fingernail collection and as such has been used to examine chronic stress in contrast to salivary or urinary cortisol which capture acute stress levels (Phillips et al. 2021). Chronically elevated cortisol levels can dysregulate the HPA axis, which leads to heightened inflammation in the body instead of the downregulation of the immune system. These findings are similar to results from studies conducted among industrialized populations where chronic stress increased inflammation via a dysregulated HPA axis (McDade, Lindau, and Wroblewski 2011; Schnall et al. 2022).

Drought is a significant environmental stressor that exacerbates existing stressors, increases resource insecurity, and thus may

TABLE 3 | Mixed-effects logistic regression model testing association of fingernail cortisol concentration and severe water insecurity on odds of elevated C-reactive protein ($n = 128$).

	Model 1	Model 2	Model 3
	CRP ≥ 1 mg/L	CRP ≥ 1 mg/L	CRP ≥ 1 mg/L
Variables	**Odds ratio 95% CI**	**Odds ratio 95% CI**	**Odds ratio 95% CI**
Fingernail cortisol concentration (ln)	2.24^{***} (1.66–3.03)		2.69^{***} (1.84–3.95)
High water insecurity (% HWISE ≥ 24)		2.25^{***} (1.25–4.05)	2.23^{***} (1.34–3.72)
Malaria infection in last 5 years (yes)			0.81 (0.52–1.26)
Household income (ln)			0.97 (0.90–1.04)
Number of times moved in last year			0.96 (0.88–1.04)
Livestock wealth (ln)			0.93^{+} (0.85–1.00)
Weekly water fetching trips (per 3)			0.71^{***} (0.59—0.85)
Individual's age (years)			0.99 (0.96–1.02)
Male (vs. female)			1.05 (0.43–2.57)
BMI (kg/m^2)			1.08 (0.92–1.28)
Observations	128	128	128

Note: Mixed effect models with observations nested within seven communities and 99 households with robust standard errors.
Abbreviations: HWISE, Household Water Insecurity Experiences scale; Ln, natural log-transformed.
$^{***}p < 0.01$, $^{**}p < 0.05$, $^{+}p < 0.1$.

contribute to increased inflammation in affected populations (Kelley et al. 2015). As water becomes scarce, pastoralist and agricultural communities worldwide struggle to access clean water for drinking, cooking, sanitation, and agriculture, resulting in heightened competition for resources and increased stress and anxiety (Aiuvalasit and Jorgeson 2024). Prolonged droughts are linked to mental health challenges, such as stress, anxiety, and depression, particularly among rural populations reliant on agriculture (Hayes et al. 2018). Chronic psychological stress due to the family environment can activate inflammatory pathways in the body, leading to increased levels of pro-inflammatory cytokines (Schreier and Chen 2017). It is likely that the drought and its effects on everyday life in Daasanach communities drove the measured cortisol concentrations. The resulting inflammatory response can exacerbate existing health conditions, leading to increased malnutrition, which in turn elevate morbidity and mortality rates among vulnerable populations (Lookadoo and Bell 2020). Additional work is needed to assess these connections to health and longevity among Daasanach.

Chronic stress increases the likelihood of future disease as a result of its effect on the immune system, including conditions such as diabetes, cardiovascular disease, and autoimmune disorders (Sapolsky 2005). Importantly, the relationship between stress and cortisol is not always linear; chronic stress can also decrease cortisol levels, which highlights the importance of contextualizing the effects of stress in specific communities and circumstances. In some cases, research has shown that severe natural disasters can result in suppressed cortisol levels many years later, or HPA burnout, as was found among survivors of the 2005 Indian Ocean tsunami (Lawton et al. 2023). This condition is potentially caused by chronic stress that results in HPA axis fatigue (Heim, Ehlert, and Hellhammer 2000; Miller, Chen, and Zhou 2007). However, in this sample of Daasanach, FCC levels were higher than those found among other small-scale populations or those dealing with stress—that is, refugees (Gettler et al. 2021; Jankovic-Rankovic et al. 2020). Specifically, the mean FCC for Daasanach in this study was 8.5 pg/mg which was higher

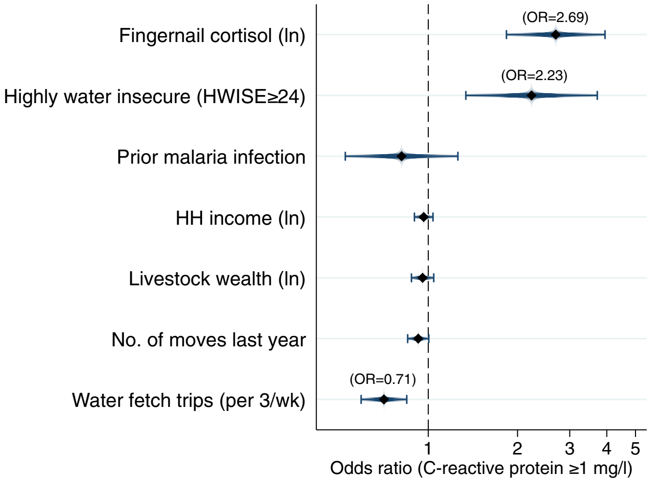

FIGURE 3 | Forest plot of mixed effect logistic regression examining the relationship between fingernail cortisol concentration, water insecurity, and covariates on odds of elevated C-reactive protein among Daasanach adults in northern Kenya. $N=128$; full model results presented in Table 3, Model 3. HWISE, Household Water Insecurity Experiences scale; Ln, natural log-transformed; No., number. wk, week.

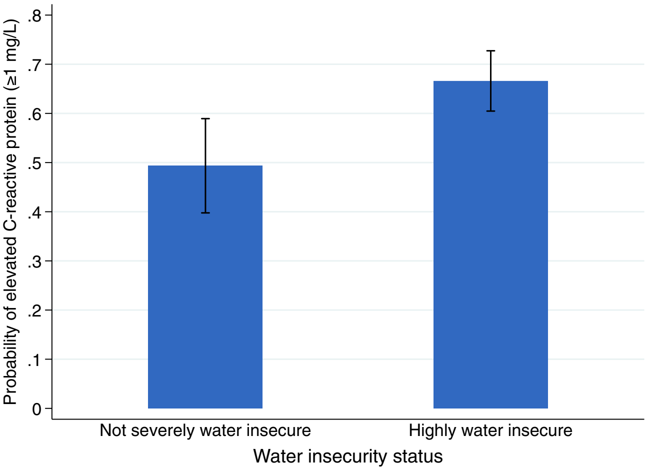

FIGURE 4 | Predicted probability of mildly elevated C-reactive protein and 95% confidence intervals by water insecurity status among Daasanach adults in northern Kenya. *Note:* Figure adjusted for the range of covariates in Table 3, Model 3, ($n=128$). Not severely water insecure defined as HWISE <24; highly water insecure defined as HWISE ≥ 24.

than adult Serbian refugees (4.4 pg/mg), adult refugees in Kukuma Refugee camp in northwestern Kenya (2.6 pg/mg), and Congolese BaYaka adults (4.4 pg/mg) (Gettler et al. 2024). Future work is needed to see how FCC levels change over time—particularly among those with higher cortisol levels observed during the drought to better understand if the levels exhibited by Daasanach in 2022 were downregulated or not.

The energy demands of immune activation can significantly impact an individual's life history by diverting finite resources away from growth and reproduction (Urlacher et al. 2018). Previous research suggests that acute increases in immune function lead to higher resting metabolic rate (Drabsch et al. 2018; Muehlenbein et al. 2010; Urlacher et al. 2019; Utaka et al. 2005). However, low-grade immune activation has been shown to contribute to negative energy balance and weight loss in certain populations (Lacourt et al. 2018; Wang and Ye 2015), which may also be expected in rural areas during droughts or periods of other environmental stress. Prior work has demonstrated that highly seasonal food supply in this environment drives extreme seasonality of births among Turkana pastoralists (Leslie and Fry 1989). Thus, inflammation may pull energy away from other critical functions (body repair, maintenance, and reproduction) among Daasanach and may contribute to malnutrition and energy deficits, thereby affecting growth and reproductive health, and increasing risk of future metabolic disease (Einarsson, Laurell, and Tiblom Ehrsson 2020; Pontzer and McGrosky 2022). Though immune responses are prioritized, high energy costs in chronic immune activation may result in life history trade-offs in the form of reduced reproduction or growth within this community (Urlacher 2023).

4.2 | Water Insecurity and Inflammation

This study found that severe water insecurity was associated with greater levels of low-grade inflammation. These findings suggest that uniquely high water insecurity experienced during drought is not only associated with greater psychosocial stress (Rosinger 2023b), but also the biological well-being of pastoralists. Water insecurity as measured by HWISE captures a suite of lived experiences related to water, from worrying about having enough water on a given day, to having enough water to cook, bath, and wash clothes and dishes, to daily interruptions due to water problems, to going to sleep thirsty. During the 2022 drought, each dimension of water insecurity was strongly affected as >90% of participants affirmed each of the 12 HWISE items (Figure S1). Thus, the multifaceted dimensions of water insecurity, including access, availability, use, and reliability captured by HWISE were all impacted (Rosinger and Young 2020). High levels of water insecurity as measured by an HWISE score of 24 or greater captures situations in which the household has responded that they sometimes experienced each of the 12 items. The present paper found that the proportion of Daasanach household heads experiencing high levels of water insecurity was 40%, which represents an increase from before the drought in 2019 when ~34% experienced severe water insecurity (Ford et al. 2023). Our prior research has demonstrated that water insecurity was associated with greater psychosocial stress and food insecurity (Bethancourt et al. 2023; Ford et al. 2023) as well as mobility ideation due to water problems, which was associated with higher FCC (Rosinger et al. 2024). This stress can further drive systemic inflammation, as supported by studies linking environmental stressors to elevated inflammatory markers like CRP (Sewpaul et al. 2019).

However, severe water insecurity is also often related to poor water quality, which can increase risk of diarrheal infections (Rosinger and Young 2020). Previous research has shown an association between environmental enteric dysfunction (EED), malnutrition, and water insecurity (Miller et al. 2021; Wu et al. 2016). Poor water quality can increase intestinal inflammation and thus elevate CRP levels via exposure to enteric pathogens and environmental contaminants (Lauer et al. 2020; Miller et al. 2021). However, our results that severe water insecurity was associated with mildly elevated CRP even when excluding those with clear active infections suggests that experiencing severe water insecurity may be a pathway leading to differentially elevated CRP levels (Figure 2). These findings indicate that supporting access to adequate and clean water, at all times, but especially during climatic stress, could alleviate some stressors related to drought-induced water insecurity, potentially reducing chronic stress and inflammation (Lauer et al. 2020; Sewpaul et al. 2019).

Extreme drought conditions can compromise water quality and availability, impacting both human health and lifestyle (Levy et al. 2016). Yet, coping strategies to water insecurity may alleviate this burden. We found that a higher number of household water fetching trips was associated with lower odds of elevated mild inflammation. Water fetching is one coping strategy used to increase water availability for a household, thereby acting as a mediator that may decrease stress induced by water insecurity. Shared water fetching within and between households, particularly for vulnerable groups like pregnant women or older adults, can act as a safety net, thereby reducing the psychosocial stress associated with water insecurity (Sadhir et al. 2024). In our study, three elderly adults who reported not fetching water had their children or grandchildren who did not live with them fetch water for them. Yet water fetching may also be associated with inflammation due to its connection to physical activity. Water fetching in the study context involves usually walking multiple hours each day and carrying heavy jerrycans. Thus, water fetching is a form of habitual physical activity, which has been shown to reduce inflammation (Kasapis and Thompson 2005). This is consistent with findings from Boateng and colleagues, who reported that implementing effective coping strategies for water insecurity can mitigate its psychosocial effects, potentially preventing increases in CRP levels (Boateng et al. 2018). Future work should examine how coping strategies to water insecurity are associated with other health outcomes.

4.3 | Extreme Climatic Events, Lifestyle Changes, and Inflammation Among Pastoralists

Michael Little (Little 1989) contended that drought is a key aspect of pastoralist life, and as such it is critical to understand the biological effects of drought and any behavioral responses that work to mitigate the negative health effects (Leslie and Little 1999). Our results demonstrate that despite living in a semiarid environment prone to drought, the experience of living through a drought still produces negative ripple effects in Daasanach biology. Drought disrupts food supplies, leading to food insecurity, which may have implications for both psychosocial stress and inflammation. Food insecurity can cause nutritional deficiencies, impairing immune function, and increasing susceptibility to infections (Cianconi, Betrò, and Janiri 2020). In our study, all participants were classified as severely food insecure, which likely contributed to both heightened stress and inflammation via nutritional insults.

Pastoralists are currently experiencing climatic changes as the pace of lifestyle transitions also accelerates, thus changing community mobility, activity patterns, and diets (Galvin 2009). Exposure to various lifestyle changes and environmental conditions has implications for inflammation processes. As Daasanach settle into more permanent communities, decreases in overall mobility lower physical activity levels, but also heighten the likelihood of encountering fecal material. Our previous research showed that actual mobility decreased in 2022 as the drought intensified compared to before the drought, even though there was a rise in mobility ideation and many individuals moved to the main market town of Illeret, where communities are less mobile (Rosinger et al. 2024). When mobility is limited among pastoralists due to climate change, socioeconomic pressures, or lifestyle transitions, pastoralists often report a greater number of health problems (Barkey, Campbell, and Leslie 2001; Lukas, Campbell, and Campbell 2005) as well as increased risk of cardiovascular disease risk factors (Lea et al. 2020; Swanson, Bethancourt, et al. 2023). In this study, we found that approximately 56% of Daasanach adults had CRP > 1 mg/L while 31% had CRP > 3 mg/L. This prevalence of elevated CRP > 3 mg/L is similar to adults living in Kukuma Refugee camp in northern Kenya (36.6%) (Gettler et al. 2024). The interactions between diet, physical activity, and exposures to pathogens are key to modulating inflammatory responses and, consequently, the risk of chronic diseases. Research shows that diets high in fruits, vegetables, whole grains, and healthy fats—which are not commonly available to Daasanach (Bethancourt et al. 2023)—have been associated with reduced inflammation (Fujita et al. 2014). Thus, in this environment, shifts in lifestyle factors like diet in combination with climatic conditions may influence inflammation and disease status (Iannotti et al. 2022).

Lifestyle transitions toward settlement in more densely populated, market-based areas have many draws including increased access to food, water, and other resources such as education and electricity (Galvin 2009; Reid, Fernández-Giménez, and Galvin 2014). However, these settlements often lack the infrastructure necessary to adequately dispose of human and animal waste. Over time, these conditions further increase the risk of coming into contact with fecal and other pathogens (Leal Filho et al. 2020; Sproston and Ashworth 2018). Prior work highlighted that in communities reliant on livestock, close interactions between humans and animals can facilitate the spread of zoonotic diseases, potentially resulting in asymptomatic infections (Asante, Noreddin, and El Zowalaty 2019; Leal Filho et al. 2020). Increased exposure to fecal pathogens can trigger immune responses and subsequently potentially lead to elevated low-grade CRP levels when this is a chronic occurrence in the way of intestinal parasites and high-grade inflammation in the event of an acute event (Ansar and Ghosh 2016). It is notable that among our covariates, increased number of moves in the prior year and greater number of times water fetching, which are both lifestyle proxies that help distinguish some level of physical activity as well as potential exposure, were associated with lower inflammation. As many in the Daasanach community rely on hand-dug wells both for their households and their livestock, sedentarization may pose a significant issue by increasing pathogenic exposure that can trigger gastrointestinal inflammation (Bell et al. 2018), but in the long-term, lead to increased risk of chronic inflammation (Lea et al. 2020).

4.4 | Strengths and Limitations

The strengths of this study include the collection of both survey and biological samples to assess conditions related to inflammation and stress, with data gathered during a period of uniquely intense water insecurity. However, as a cross-sectional analysis from one time point, it is limited in its ability to infer causality. Additionally, it is unable to distinguish between chronic inflammation and acute inflammation. Prior work with small-scale populations suggests that CRP levels ≥ 1 mg/L generally represent mild, but costly acute inflammation as there is limited evidence of chronic inflammation in those populations (Mcdade et al. 2012; Urlacher et al. 2018). However, our results were mostly consistent when using a 3 mg/L cutoff and when excluding participants who may have had active infections; thus, we cannot rule out that chronic stress from drought conditions and severe water insecurity may lead to differential CRP profiles. The sensitivity analysis using CRP ≥ 3 mg/L as the cutoff likely captures individuals experiencing acute-phase inflammation that may introduce error into the analysis. Second, the statistical power is likely reduced with fewer individuals in the elevated category and a less balanced sample—thus potentially explaining why high WI was no longer associated with elevated CRP in the linear models and the sensitivity analysis. Additionally, as we only have fingernails from one timepoint in 2022 and due to the fact that FCC averages cortisol levels over the period reflective of the fingernails, here designed to capture the height of the drought, it is not able to distinguish changes in cortisol levels within individuals. Future research should investigate how these stressors impact direct measures of cardiometabolic health, other biomarkers, including additional measures of inflammation (e.g., pro-inflammatory cytokines) and gastrointestinal microbiomes as well as the risk of noncommunicable diseases in pastoralist communities. Similarly, future research should explore how sexual division of labor and increasing market integration affects these relationships.

5 | Conclusion

In this study, we found that higher FCC and severe water insecurity were significantly associated with elevated circulating CRP during a historic drought in northern Kenya. This study provides additional evidence for how an extreme drought negatively affects pastoralists' biology through the complex relationships between chronic stress, water insecurity, and inflammation. More broadly, these results highlight how exposures to extreme climatic events can negatively influence the well-being and health of these populations. The impact of drought on human health is a pressing global health issue, especially among marginalized and under-resourced populations who already face health and economic disparities and are likely to bear the brunt of climate change. This is particularly important to understand given the central role of inflammation in the etiology of cardiometabolic and other noncommunicable diseases that are rising rapidly in low- and middle-income countries. Multisectoral strategic investments are needed in reliable and safe water sources, particularly in areas experiencing severe water insecurity, to foster resilience in communities facing the effects of climate change.

Author Contributions

Asher Y. Rosinger: funding acquisition, conceptualization (lead), data collection, formal analysis, drafting, and editing (lead). **Kedir Teji Roba:** conceptualization (supporting), methodology (supporting), writing – review (lead). **Hannah Jacobson, Amanda McGrosky, and Samuel S. Urlacher:** conceptualization (supporting), methodology (supporting), writing – review and editing (supporting). **Srishti Sadhir and Leslie B. Ford:** data collection (supporting), writing – review and editing (supporting). **Marcela Pfaff, Elizabeth Y. Kim, Rosemary Nzunza, and Matthew Douglass:** data collection (supporting), methodology (supporting). **David R. Braun:** funding acquisition, writing – review and editing (supporting). **Emmanuel Ndiema:** funding acquisition, methodology (supporting), writing – review and editing (supporting). **Herman Pontzer:** funding acquisition, conceptualization (supporting), data collection, writing – review and editing (supporting).

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

References

Aiuvalasit, M. J., and I. A. Jorgeson. 2024. "Combining Paleohydrology and Least-Cost Analyses to Assess the Vulnerabilities of Ancestral Pueblo Communities to Water Insecurity in the Jemez Mountains, New Mexico." *American Antiquity* 89: 58–77.

Ansar, W., and S. Ghosh. 2016. "Inflammation and Inflammatory Diseases, Markers, and Mediators: Role of CRP in Some Inflammatory Diseases." In *Biology of C Reactive Protein in Health and Disease*, 67–107. Springer India.

Anyah, R. O., and W. Qiu. 2012. "Characteristic 20th and 21st Century Precipitation and Temperature Patterns and Changes Over the Greater Horn of Africa." *International Journal of Climatology* 32: 347–363.

Apanius, V. 1998. "Stress and Immune Defense." In *Advances in the Study of Behavior*, vol. 27, 133–153. Elsevier.

Asante, J., A. Noreddin, and M. E. El Zowalaty. 2019. "Systematic Review of Important Bacterial Zoonoses in Africa in the Last Decade in Light of the 'One Health' Concept." *Pathogens* 8: 50.

Avan, A., S. B. Tavakoly Sany, M. Ghayour-Mobarhan, H. R. Rahimi, M. Tajfard, and G. Ferns. 2018. "Serum C-Reactive Protein in the Prediction of Cardiovascular Diseases: Overview of the Latest Clinical Studies and Public Health Practice." *Journal of Cellular Physiology* 233: 8508–8525.

Barkey, N. L., B. C. Campbell, and P. W. Leslie. 2001. "A Comparison of Health Complaints of Settled and Nomadic Turkana Men." *Medical Anthropology Quarterly* 15: 391–408.

Bell, J. E., C. L. Brown, K. Conlon, et al. 2018. "Changes in Extreme Events and the Potential Impacts on Human Health." *Journal of the Air & Waste Management Association* 68: 265–287.

Bethancourt, H. J., Z. S. Swanson, R. Nzunza, et al. 2021. "Hydration in Relation to Water Insecurity, Heat Index, and Lactation Status in Two Small-Scale Populations in Hot-Humid and Hot-Arid Environments." *American Journal of Human Biology* 33: e23447.

Bethancourt, H. J., Z. S. Swanson, R. Nzunza, et al. 2023. "The Co-Occurrence of Water Insecurity and Food Insecurity Among Daasanach Pastoralists in Northern Kenya." *Public Health Nutrition* 26: 693–703.

Blackwell, A. D., J. J. Snodgrass, F. C. Madimenos, and L. S. Sugiyama. 2010. "Life History, Immune Function, and Intestinal Helminths: Trade-Offs Among Immunoglobulin E, C-Reactive Protein, and Growth in an Amazonian Population." *American Journal of Human Biology* 22: 836–848.

Boateng, G. O., S. M. Collins, P. Mbullo, et al. 2018. "A Novel Household Water Insecurity Scale: Procedures and Psychometric Analysis Among Postpartum Women in Western Kenya." *PLoS One* 13: e0198591.

Chang, J., A. Guo, Y. Wang, et al. 2019. "Reservoir Operations to Mitigate Drought Effects With a Hedging Policy Triggered by the Drought Prevention Limiting Water Level." *Water Resources Research* 55: 904–922.

Chen, E. Y., C. R. Homolka, J. S. Meyer, and L. T. Gettler. 2023. "A Small, Exploratory Analysis of Fingernail Cortisol, Psychosocial Well-Being, and Social Support Among Undergraduate Students During the COVID-19 Pandemic." *Adaptive Human Behavior and Physiology* 9: 198–215.

Cianconi, P., S. Betrò, and L. Janiri. 2020. "The Impact of Climate Change on Mental Health: A Systematic Descriptive Review." *Frontiers in Psychiatry* 11: 490206.

Coussons-Read, M. E., M. L. Okun, and C. D. Nettles. 2007. "Psychosocial Stress Increases Inflammatory Markers and Alters Cytokine Production Across Pregnancy." *Brain, Behavior, and Immunity* 21: 343–350.

Davison, B., G. R. Singh, V. M. Oguoma, and J. McFarlane. 2020. "Fingernail Cortisol as a Marker of Chronic Stress Exposure in Indigenous and Non-Indigenous Young Adults." *Stress* 23: 298–307.

Dhabhar, F. S. 2008. "Enhancing Versus Suppressive Effects of Stress on Immune Function: Implications for Immunoprotection Versus Immunopathology." *Allergy, Asthma & Clinical Immunology* 4: 2–11.

Drabsch, T., C. Holzapfel, L. Stecher, J. Petzold, T. Skurk, and H. Hauner. 2018. "Associations Between C-Reactive Protein, Insulin Sensitivity, and Resting Metabolic Rate in Adults: A Mediator Analysis." *Frontiers in Endocrinology* 9: 556. https://doi.org/10.3389/fendo.2018.00556.

Ebi, K. L., and K. Bowen. 2016. "Extreme Events as Sources of Health Vulnerability: Drought as an Example." *Weather and Climate Extremes* 11: 95–102.

Einarsson, S., G. Laurell, and Y. Tiblom Ehrsson. 2020. "An Explorative Study on Energy Balance in Patients With Head and Neck Cancer." *Nutrition and Cancer* 72: 1191–1199.

Eriksson, U. K., D. van Bodegom, L. May, A. G. C. Boef, and R. G. J. Westendorp. 2013. "Low C-Reactive Protein Levels in a Traditional West-African Population Living in a Malaria Endemic Area." *PLoS One* 8: e70076.

Firkey, M. K., L. K. Tully, V. M. Bucci, et al. 2023. "Feasibility of Remote Self-Collection of Dried Blood Spots, Hair, and Nails Among People With HIV With Hazardous Alcohol Use." *Alcohol: Clinical and Experimental Research* 47: 986–995.

Ford, L. B., H. J. Bethancourt, Z. S. Swanson, et al. 2023. "Water Insecurity, Water Borrowing and Psychosocial Stress Among Daasanach Pastoralists in Northern Kenya." *Water International* 48: 63–86.

Fratkin, E. 2013. "Seeking Alternative Livelihoods in Pastoral Areas." In *Pastoralism and Development in Africa*, 217–225. Routledge.

Frongillo, E. A., H. J. Bethancourt, J. D. Miller, and S. L. Young. 2024. "Identifying Ordinal Categories for the Water Insecurity Experiences Scales." *Journal of Water Sanitation and Hygiene for Development* 14, no. 11: washdev2024042. https://doi.org/10.2166/washdev.2024.042.

Fujita, M., E. Brindle, Y. Lo, P. Castro, and F. Cameroamortegui. 2014. "Nutrient Intakes Associated With Elevated Serum C-Reactive Protein Concentrations in Normal to Underweight Breastfeeding Women in Northern K Enya." *American Journal of Human Biology* 26: 796–802.

Galvin, K. A. 1992. "Nutritional Ecology of Pastoralists in Dry Tropical Africa." *American Journal of Human Biology* 4: 209–221.

Galvin, K. A. 2009. "Transitions: Pastoralists Living With Change." *Annual Review of Anthropology* 38: 185–198.

Gebre, Y. 2012. "Environmental Change, Food Crises and Violence in Dassanech, Southern Ethiopia."

Gettler, L. T., J. Jankovic-Rankovic, R. G. Gengo, et al. 2024. "Refugee Health and Physiological Profiles in Transitional Settlements in Serbia and Kenya: Comparative Evidence for Effects of Gender and Social Support." *Psychoneuroendocrinology* 165: 107024.

Gettler, L. T., S. Lew-Levy, M. S. Sarma, et al. 2021. "Children's Fingernail Cortisol Among BaYaka Foragers of the Congo Basin: Associations With Fathers' Roles." *Philosophical Transactions of the Royal Society, B: Biological Sciences* 376: 20200031.

Goosby, B. J., S. Malone, E. A. Richardson, J. E. Cheadle, and D. T. Williams. 2015. "Perceived Discrimination and Markers of Cardiovascular Risk Among Low-Income African American Youth." *American Journal of Human Biology* 27: 546–552.

Hayes, K., G. Blashki, J. Wiseman, S. Burke, and L. Reifels. 2018. "Climate Change and Mental Health: Risks, Impacts and Priority Actions." *International Journal of Mental Health Systems* 12: 1–12.

Heidari, H., and D. A. Lawrence. 2023. "Climate Stressors and Physiological Dysregulations: Mechanistic Connections to Pathologies." *International Journal of Environmental Research and Public Health* 21: 28.

Heim, C., U. Ehlert, and D. H. Hellhammer. 2000. "The Potential Role of Hypocortisolism in the Pathophysiology of Stress-Related Bodily Disorders." *Psychoneuroendocrinology* 25: 1–35.

Iannotti, L., C. Lesorogol, C. Hilton, et al. 2022. "Mineral Nutrition of Samburu Adolescents: A Comparative Study of Pastoralist Communities in Kenya." *American Journal of Biological Anthropology* 177: 343–356.

Jankovic-Rankovic, J., R. C. Oka, J. S. Meyer, and L. T. Gettler. 2020. "Forced Migration Experiences, Mental Well-Being, and Nail Cortisol Among Recently Settled Refugees in Serbia." *Social Science & Medicine* 258: 113070.

Johnson, T. V., A. Abbasi, and V. A. Master. 2013. "Systematic Review of the Evidence of a Relationship Between Chronic Psychosocial Stress and C-Reactive Protein." *Molecular Diagnosis & Therapy* 17: 147–164.

Kaptoge, S. A., E. di Angelantonio, G. Lowe, et al. 2010. "C-Reactive Protein Concentration and Risk of Coronary Heart Disease, Stroke, and Mortality: An Individual Participant Meta-Analysis." *Lancet* 375, no. 9709: 132–140. https://doi.org/10.1016/s0140-6736(09)61717-7.

Kasapis, C., and P. D. Thompson. 2005. "The Effects of Physical Activity on Serum C-Reactive Protein and Inflammatory Markers." *Journal of the American College of Cardiology* 45: 1563–1569.

Kelley, C. P., S. Mohtadi, M. A. Cane, R. Seager, and Y. Kushnir. 2015. "Climate Change in the Fertile Crescent and Implications of the Recent Syrian Drought." *Proceedings of the National Academy of Sciences of the United States of America* 112: 3241–3246.

Kiura, P. W. 2005. *An Ethnoarchaeology and Stable Isotope Study on the Diets of Three Modern Groups of People in Northern Kenya*. Rutgers School of Graduate Studies, The State University of New Jersey.

KNBS. 2019. *The 2009 Kenya Population and Housing Census*. Kenya National Bureau of Statistics.

Lacourt, T. E., E. G. Vichaya, G. S. Chiu, R. Dantzer, and C. J. Heijnen. 2018. "The High Costs of Low-Grade Inflammation: Persistent Fatigue as a Consequence of Reduced Cellular-Energy Availability and Non-Adaptive Energy Expenditure." *Frontiers in Behavioral Neuroscience* 12: 78. https://doi.org/10.3389/fnbeh.2018.00078.

Lauer, J. M., S. Ghosh, L. M. Ausman, et al. 2020. "Markers of Environmental Enteric Dysfunction Are Associated With Poor Growth and Iron Status in Rural Ugandan Infants." *Journal of Nutrition* 150: 2175–2182.

Lawton, R., E. Frankenberg, T. Seeman, E. Crimmins, C. Sumantri, and D. Thomas. 2023. "Exposure to the Indian Ocean Tsunami Shapes the HPA-Axis Resulting in HPA "Burnout" 14 Years Later." *Proceedings of the National Academy of Sciences* 120: e2306497120.

Lea, A. J., D. Martins, J. Kamau, M. Gurven, and J. F. Ayroles. 2020. "Urbanization and Market Integration Have Strong, Nonlinear Effects on Cardiometabolic Health in the Turkana." *Science Advances* 6: eabb1430.

Leal Filho, W., H. Taddese, M. Balehegn, et al. 2020. "Introducing Experiences From African Pastoralist Communities to Cope With Climate Change Risks, Hazards and Extremes: Fostering Poverty Reduction." *International Journal of Disaster Risk Reduction* 50: 101738.

Leslie, P. W., and P. H. Fry. 1989. "Extreme Seasonality of Births Among Nomadic Turkana Pastoralists." *American Journal of Physical Anthropology* 79: 103–115.

Leslie, P. W., and M. A. Little. 1999. *Turkana Herders of the Dry Savanna: Ecology and Biobehavioral Response of Nomads to an Uncertain Environment*. Oxford University Press on Demand.

Levy, K., A. P. Woster, R. S. Goldstein, and E. J. Carlton. 2016. "Untangling the Impacts of Climate Change on Waterborne Diseases: A Systematic Review of Relationships Between Diarrheal Diseases and Temperature, Rainfall, Flooding, and Drought." *Environmental Science & Technology* 50: 4905–4922.

Little, M. A. 1989. "Human Biology of African Pastoralists." *American Journal of Physical Anthropology* 32: 215–247.

Lookadoo, R. E., and J. E. Bell. 2020. "Public Health Policy Actions to Address Health Issues Associated With Drought in a Changing Climate." *Journal of Law, Medicine & Ethics* 48: 653–663.

Lukas, W. D., B. C. Campbell, and K. L. Campbell. 2005. "Urinary Cortisol and Muscle Mass in Turkana Men." *American Journal of Human Biology: The Official Journal of the Human Biology Association* 17: 489–495.

McDade, T. W., J. Burhop, and J. Dohnal. 2004. "High-Sensitivity Enzyme Immunoassay for C-Reactive Protein in Dried Blood Spots." *Clinical Chemistry* 50: 652–654.

McDade, T. W., S. T. Lindau, and K. Wroblewski. 2011. "Predictors of C-Reactive Protein in the National Social Life, Health, and Aging Project." *Journals of Gerontology. Series B, Psychological Sciences and Social Sciences* 66: 129–136.

Mcdade, T. W., P. S. Tallman, F. C. Madimenos, et al. 2012. "Analysis of Variability of High Sensitivity C-Reactive Protein in Lowland Ecuador Reveals No Evidence of Chronic Low-Grade Inflammation." *American Journal of Human Biology* 24: 675–681.

McDade, T. W., S. Williams, and J. J. Snodgrass. 2007. "What a Drop Can Do: Dried Blood Spots as a Minimally Invasive Method for Integrating Biomarkers Into Population-Based Research." *Demography* 44: 899–925.

McGrosky, A., Z. S. Swanson, R. Rimbach, et al. 2024. "Total Daily Energy Expenditure and Elevated Water Turnover in a Small-Scale Semi-Nomadic Pastoralist Society From Northern Kenya." *Annals of Human Biology* 51: 2310724.

Megersa, B., A. Markemann, A. Angassa, J. O. Ogutu, H.-P. Piepho, and A. V. Zaráte. 2014. "Impacts of Climate Change and Variability on Cattle Production in Southern Ethiopia: Perceptions and Empirical Evidence." *Agricultural Systems* 130: 23–34.

Miller, D. B., and J. P. O'Callaghan. 2002. "Neuroendocrine Aspects of the Response to Stress." *Metabolism-Clinical and Experimental* 51: 5–10.

Miller, G. E., E. Chen, and E. S. Zhou. 2007. "If It Goes Up, Must It Come Down? Chronic Stress and the Hypothalamic-Pituitary-Adrenocortical Axis in Humans." *Psychological Bulletin* 133: 25–45.

Miller, J. D., C. L. Workman, S. V. Panchang, et al. 2021. "Water Security and Nutrition: Current Knowledge and Research Opportunities." *Advances in Nutrition* 12: 2525–2539.

Muehlenbein, M. P., J. L. Hirschtick, J. Z. Bonner, and A. M. Swartz. 2010. "Toward Quantifying the Usage Costs of Human Immunity: Altered Metabolic Rates and Hormone Levels During Acute Immune Activation in Men." *American Journal of Human Biology* 22: 546–556.

Muheki, D., A. A. J. Deijns, E. Bevacqua, G. Messori, J. Zscheischler, and W. Thiery. 2024. "The Perfect Storm? Co-Occurring Climate Extremes in East Africa." *Earth System Dynamics* 15: 429–466.

Mwamidi, D. M., J. G. Renom, A. F. Llamazares, D. Burgas, P. Domínguez, and M. Cabeza. 2018. "Contemporary Pastoral Commons in East Africa as OECMs: A Case Study From Daasanach Community." *Parks Recreation* 24: 49–58.

Peto, T. J., R. Tripura, S. J. Lee, et al. 2016. "Association Between Subclinical Malaria Infection and Inflammatory Host Response in a Pre-Elimination Setting." *PLoS One* 11: e0158656.

Phillips, R., A.-K. Kraeuter, B. McDermott, S. Lupien, and Z. Sarnyai. 2021. "Human Nail Cortisol as a Retrospective Biomarker of Chronic Stress: A Systematic Review." *Psychoneuroendocrinology* 123: 104903.

Pontzer, H., and A. McGrosky. 2022. "Balancing Growth, Reproduction, Maintenance, and Activity in Evolved Energy Economies." *Current Biology* 32: R709–R719.

Pörtner, H., D. Roberts, H. Adams, et al. 2023. "SPM-Summary for Policymakers."

Reid, R. S., M. E. Fernández-Giménez, and K. A. Galvin. 2014. "Dynamics and Resilience of Rangelands and Pastoral Peoples Around the Globe." *Annual Review of Environment and Resources* 39: 217–242.

Ridker, P. M., and D. A. Morrow. 2003. "C-Reactive Protein, Inflammation, and Coronary Risk." *Cardiology Clinics* 21: 315–325.

Rohleder, N. 2019. "Stress and Inflammation—The Need to Address the Gap in the Transition Between Acute and Chronic Stress Effects." *Psychoneuroendocrinology* 105: 164–171.

Rosinger, A. Y. 2023a. "Extreme Climatic Events and Human Biology and Health: A Primer and Opportunities for Future Research." *American Journal of Human Biology* 35: e23843.

Rosinger, A. Y. 2023b. "Water Needs, Water Insecurity, and Human Biology." *Annual Review of Anthropology* 52: 93–113.

Rosinger, A. Y., H. Bethancourt, Z. S. Swanson, et al. 2021. "Drinking Water Salinity Is Associated With Hypertension and Hyperdilute Urine Among Daasanach Pastoralists in Northern Kenya." *Science of the Total Environment* 770: 144667.

Rosinger, A. Y., J. Stoler, L. B. Ford, et al. 2024. "Mobility Ideation due to Water Problems During Historic 2022 Drought Associated With Livestock Wealth, Water and Food Insecurity, and Fingernail Cortisol Concentration in Northern Kenya." *Social Science & Medicine* 359: 117280.

Rosinger, A. Y., and S. L. Young. 2020. "The Toll of Household Water Insecurity on Health and Human Biology: Current Understandings and Future Directions." *Wiley Interdisciplinary Reviews: Water* 7: e1468.

Sadhir, S., A. McGrosky, B. Ford Leslie, et al. 2024. "Physical Activity and Pregnancy Norms Among Daasanach Semi-Nomadic Pastoralist Women in Northern Kenya." *American Journal of Human Biology* 37: e24174.

Sapolsky, R. 2005. "Sick of Poverty." *Scientific American* 293: 92–99.

Schnall, R., J. Liu, E. Cordoba, et al. 2022. "Differences in Self-Reported Stress Versus. Hair and Nail Cortisol Among Adolescent and Young Adult Males." *Nursing Research* 73: 442–449.

Schreier, H. M., and E. Chen. 2017. "Low-Grade Inflammation and Ambulatory Cortisol in Adolescents: Interaction Between Interviewer-Rated Versus Self-Rated Acute Stress and Chronic Stress." *Psychosomatic Medicine* 79: 133–142.

Sewpaul, R., P. J. Naudé, D. J. Stein, and D. Labadarios. 2019. "Psychological Distress and C-Reactive Protein in a South African National Survey." *Acta Neuropsychiatrica* 31: 270–275.

Sproston, N. R., and J. J. Ashworth. 2018. "Role of C-Reactive Protein at Sites of Inflammation and Infection." *Frontiers in Immunology* 9: 754.

Straight, B., C. E. Hilton, A. Naugle, et al. 2022. "Drought, Psychosocial Stress, and Ecogeographical Patterning: Tibial Growth and Body Shape in Samburu (Kenyan) Pastoralist Children." *American Journal of Biological Anthropology* 178: 574–592.

Swanson, Z. S., H. Bethancourt, R. Nzunza, et al. 2023. "The Effects of Lifestyle Change on Indicators of Cardiometabolic Health in Semi-Nomadic Pastoralists." *Evolution, Medicine, and Public Health* 11: 318–331.

Swanson, Z. S., R. Nzunza, H. J. Bethancourt, et al. 2023. "Early Childhood Growth in Daasanach Pastoralists of Northern Kenya: Distinct Patterns of Faltering in Linear Growth and Weight Gain." *American Journal of Human Biology* 35: e23842.

Tallman, P. S., S. M. Collins, M. P. Chaparro, and G. Salmon-Mulanovich. 2022. "Water Insecurity, Self-Reported Physical Health, and Objective Measures of Biological Health in the Peruvian Amazon." *American Journal of Human Biology* 34: e23805.

Tavares, J. P., L. Lautert, T. S. B. S. Magnago, A. R. Consiglio, and D. D. Pai. 2017. "Relationship Between Psychosocial Stress Dimensions and Salivary Cortisol in Military Police Officers." *Revista Latino-Americana de Enfermagem* 25: e2s873.

Tierney, J. E., C. C. Ummenhofer, and P. B. Demenocal. 2015. "Past and Future Rainfall in the Horn of Africa." *Science Advances* 1: e1500682.

Urlacher, S. S. 2023. "The Energetics of Childhood: Current Knowledge and Insights Into Human Variation, Evolution, and Health." *American Journal of Biological Anthropology* 181: 94–117.

Urlacher, S. S., P. T. Ellison, L. S. Sugiyama, et al. 2018. "Tradeoffs Between Immune Function and Childhood Growth Among Amazonian Forager-Horticulturalists." *Proceedings of the National Academy of Sciences* 115: E3914–E3921.

Urlacher, S. S., J. J. Snodgrass, L. R. Dugas, et al. 2019. "Constraint and Trade-Offs Regulate Energy Expenditure During Childhood." *Science Advances* 5: eaax1065.

Utaka, S., C. M. Avesani, S. A. Draibe, M. A. Kamimura, S. Andreoni, and L. Cuppari. 2005. "Inflammation Is Associated With Increased Energy Expenditure in Patients With Chronic Kidney Disease." *American Journal of Clinical Nutrition* 82: 801–805.

Verschuren, D., K. R. Laird, and B. F. Cumming. 2000. "Rainfall and Drought in Equatorial East Africa During the Past 1,100 Years." *Nature* 403: 410–414.

Voegel, C. D., P. La Marca-Ghaemmaghami, U. Ehlert, M. R. Baumgartner, T. Kraemer, and T. M. Binz. 2018. "Steroid Profiling in Nails Using Liquid Chromatography-Tandem Mass Spectrometry." *Steroids* 140: 144–150.

Wan, W., J. Zhao, H. Y. Li, et al. 2017. "Hydrological Drought in the Anthropocene: Impacts of Local Water Extraction and Reservoir Regulation in the US." *Journal of Geophysical Research: Atmospheres* 122: 11–313.

Wang, H., and J. Ye. 2015. "Regulation of Energy Balance by Inflammation: Common Theme in Physiology and Pathology." *Reviews in Endocrine and Metabolic Disorders* 16: 47–54.

WHO. 2023. *Region Regional Bureau for the East and Horn of Africa, and the Great Lakes Region (unhcr.org) Source: UNHCR, COR, IPP (31 December 2023).* World Health Organization.

Wilairatana, P., P. Mahannop, T. Tussato, et al. 2021. "C-Reactive Protein as an Early Biomarker for Malaria Infection and Monitoring of Malaria Severity: A Meta-Analysis." *Scientific Reports* 11: 22033.

Williams, R. 2012. "Using the Margins Command to Estimate and Interpret Adjusted Predictions and Marginal Effects." *Stata Journal* 12: 308–331.

Wu, J., M. Yunus, M. S. Islam, and M. Emch. 2016. "Influence of Climate Extremes and Land Use on Fecal Contamination of Shallow Tubewells in Bangladesh." *Environmental Science & Technology* 50: 2669–2676.

Yang, H., F. Ma, and X. Yuan. 2023. "The Role of Human Activities in the Weakening of the Propagation Relationship Between Meteorological and Hydrological Droughts in the Heihe River Basin." *Hydrological Processes* 37: e14946.

Young, S. L., G. O. Boateng, Z. Jamaluddine, et al. 2019. "The Household Water InSecurity Experiences (HWISE) Scale: Development and Validation of a Household Water Insecurity Measure for Low-Income and Middle-Income Countries." *BMJ Global Health* 4: e001750.

Supporting Information

Additional supporting information can be found online in the Supporting Information section.