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Building an interdisciplinary framework to advance conceptual and technical aspects of population-environment research focused on women's and children's health

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ABSTRACT

Great gains have been made in providing researchers geo-spatial data that can be combined with population health data. This development is crucial given concerns over the human health outcomes associated with a changing climate. Merging population and environmental data remains both conceptually and technically challenging because of a large range of temporal and spatial scales. Here we propose a framework that addresses and advances both conceptual and technical aspects of population-environment research. This framework can be useful for considering how any time or space-based environmental occurrence influences population health outcomes and can be used to guide different data aggregation strategies. The primary consideration discussed here is how to properly model the space and time effects of environmental context on individual-level health outcomes, specifically maternal, child and reproductive health outcomes. The influx of geospatial health data and highly detailed environmental data, often at daily scales, provide an opportunity for population-environment researchers to move towards a more theoretically and analytically sound approach for studying environment and health linkages.

1. Introduction

Environmental data like rainfall or temperature data or drought or vegetation indices are widely used in the physical sciences to describe and investigate trends over time and to define and identify extreme events. These data are often available as daily measures (daily maximum temperature, for example) or 5–7 day composite measures (vegetation/greenness indices and total rainfall, for example). In terms of spatial scale, environmental data are increasingly available at spatial scales of less than 1 m (vegetation) but are also commonly available at much coarser scales closer to 25–50 km in resolution. Investments in tools like Google Earth Engine have facilitated access to these massive global data sets and allow a user to determine the time period and spatial and temporal scale of the available data for a given country or community. At the same time, including the latitude and longitude of a community or household has become routine in population surveys related to health and development. On their own, each type of data – population survey data and environmental data - is important and widely used within specific disciplines. In combination, however, these data can be used to help answer some of today's pressing questions about the human impacts of climate change.

Without doubt, these widely (and freely) available georeferenced data provide the necessary foundation for investigating questions related to health and development in a context of a changing climate. This development is crucial given concerns over climate change and extreme events and the increasing importance of understanding the ways that context influences population health. However, the dramatically different spatial and temporal scales of the data can make straightforward data merging very complicated and analysts must make choices that affect how well the empirical analysis aligns with the research question.

To manage and analyze the vast array of data with varying temporal and spatial scales, we argue that interdisciplinary population-environment scholars need to consider and identify the mechanisms that link climate change characteristics to health outcomes when aggregating and merging data. To maximize the opportunities provided by combining these resources, we draw on theoretical and methodological developments from multiple disciplines to propose a framework that advances both conceptual and technical aspects of population-

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environment research. This framework, which can be modified to fit the specific research question and data of interest, can also be used to guide data aggregation strategies which is especially important to consider when working with daily environmental data and cross-section population data. In other words, our framework can serve as a useful starting point for interdisciplinary scholars asking questions like "*how do I assess the relationship between temperature and infant mortality?"* We posit that the answer to questions such as this is found in the framework that the researcher uses to guide their research and we develop such a framework here. Our proposed approach merges elements from concepts of 'exposure-dose-response' and exposure types from Public Health, Geography's focus on spatial context and Sociology's life-course theory.

We discuss distinct processes through which the environment impacts human health, either directly or indirectly[1] (Grace, 2017; Victora et al., 2008; Carleton and Hsiang, 2016), with attention to the unique spatial and temporal footprints that correspond to different types of impacts. To offer insight into mechanisms that are relevant for policymakers and that can be considered in both quantitative and qualitative approaches, we argue that proper modeling of these linkages requires careful analytical design, including alignment of measures and models with the research question while accounting for the geographical and temporal embeddedness of exposure and individuals' experiences.

We demonstrate the utility of our interdisciplinary approach as applied to maternal reproductive and child health (MRCH) research. This growing literature is particularly characterized by vaguely or broadly defined mechanistic links. Inconsistencies in quantitative results found in the literature may result from the differing strategies used to operationalize environmental and contextual features when combining climate, geospatial, and population health data. The remainder of the paper proceeds as follows: we first discuss existing literature and highlight commonalities and differences in approach as well as results, we then explore the concept of exposure, highlight five distinct environmental exposure models that capture the most commonly theorized stressors, and explain the need for a life course approach. Next, we discuss the utility of an integrated approach of these concepts. Finally, we graphically depict the inter-related framework with empirical examples relevant to MRCH research, where we allow the exposure models to reflect either direct or indirect connections to environmental context.

2. Different approaches yield different results

An ideal study can produce results capable of differentiating and quantifying variability in MRCH outcomes that are separately attributable to direct and indirect linkages at different key periods in the lives of women and children. This is an important contribution because it allows scientists to differentiate the causes and effects of different climate-health linkages and supports the development of mitigation policies that address the specific processes leading to the adverse health outcome among the neediest individuals (McMichael, 2013; Patz et al. 2014). Differences in available data, approach (including specifying the mechanism under study), and interpretation of results has, however, led to a rapidly growing body of scholarship with varying results and interpretations (Amegah et al., 2016; McMichael et al., 2006; Phalkey et al., 2015).

A common approach is for analysts to investigate environmental effects on a single MRCH outcome and use the results as an indicator of how environment impacts MRCH more broadly. Most research investigating environmental effects on a particular MRCH outcome has typically focused on wealthy countries, but a growing body of literature is using health survey data to investigate the ways that environmental factors impact MRCH outcomes in the poorest countries in the world (Watts et al., 2015). When studies focus on sub-Saharan Africa and other developing regions, food insecurity or disease exposure are frequently cited as the likely linkages between climate/weather and health outcomes and heat stress is often identified as the direct linkage (for example, Grace et al., 2012; de Sherbinin, 2011; Bakhtsiyarava et al., 2018; Shively, 2017, McMichael, 2013). However, as noted in several review articles, the strategies used to operationalize the climate variables vary dramatically (McMichael et al., 2006; Amegah et al., 2016). Spatial and temporal aggregation are key requirements as the spatial and temporal scale of the health survey data never exactly align with the scales of the environmental data. Among the approaches used, some analyses focus on monthly averages over the life of an individual, some focus on climate extremes, and some focus on specific periods (the growing season, for example) (see Grace et al., 2017, Watts et al., 2015). Other approaches include incorporating the long-term mean, standard deviation or flagging climate anomalies (Bashktiyarava et al. 2018; Brown et al., 2015; Kinyoki et al., 2016).

Some scholars justify why they adopted specific approaches to temporal aggregation (for example, "we specifically focus on growing season characteristics"), while others provide little insight into why they aggregated the data in the ways that they did. Some focus on recent events (a particular type of shock) while others consider average conditions over a long or short period of time. In the reviews of recent articles that consider the effects of environmental conditions on children's health outcomes in poor countries, for example, distinct statistical differences arise when comparing results from the cited empirical research (Amegah et al., 2016; Phalkey et al., 2015). Monthly, weekly or seasonal temperature conditions are used and rainfall means and variability is used. Naturally, given the different approaches, results differ in statistically significant ways and, at times, even indicate different magnitudes as well as direction of effects. In the same or similar settings, different approaches indicate different relationships between health outcomes and either rainfall or temperature (Amegah et al., 2016; Phalkey et al., 2015). Decisions surrounding merging environmental data to individual data are also not often clear, with analysts seemingly making choices based on the best of what they have (e.g., regional or country level data, cross-sectional individual level data) or based on commonly used approaches (see Grace et al., 2019). With fine spatial scale environmental data becoming easier to access and use researchers now have to carefully consider the appropriate spatial scales to use as well.

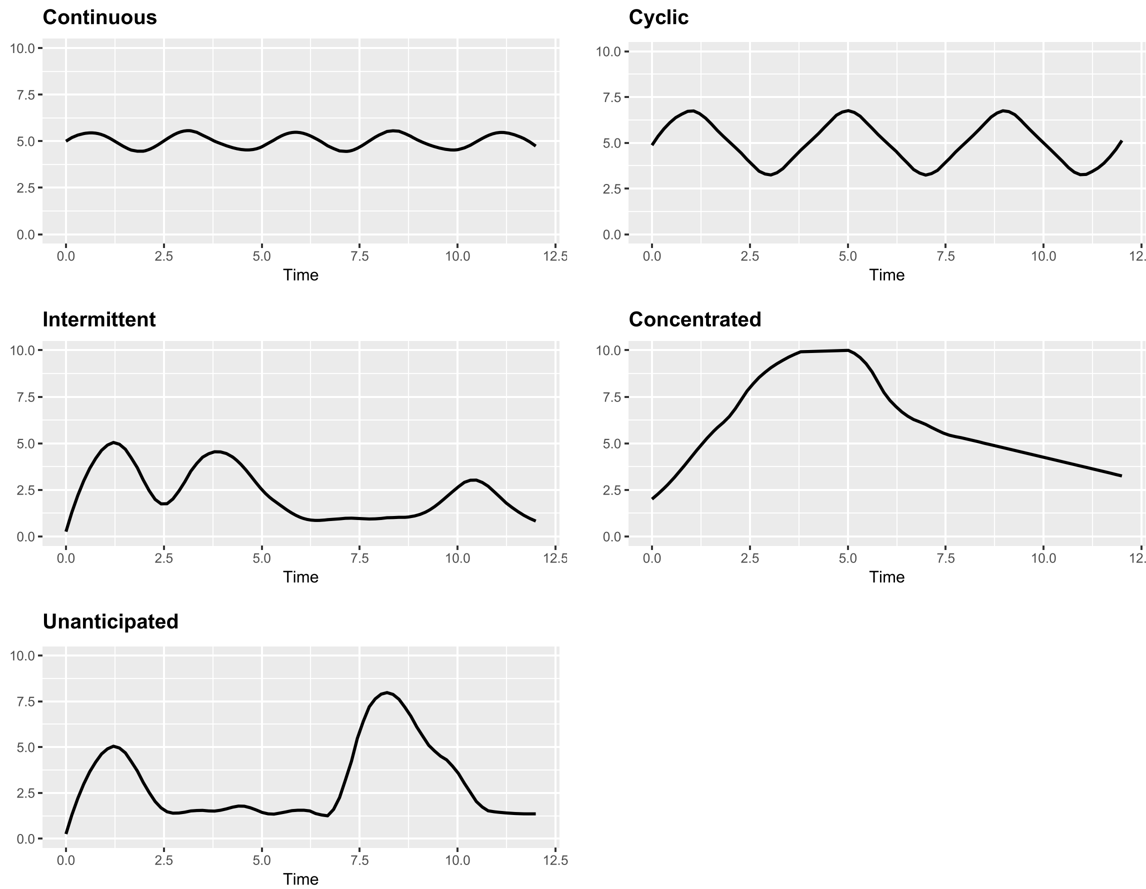
Ultimately, these coarse or vaguely described approaches make it difficult to determine the nature of the relationship and the underlying driver of the health outcome associated with the climate or environmental measures (Phalkey et al., 2015). Without clearer framing that addresses the relevant spatial footprint within a given time period, identifying the linkage between exposure timing and exposure type is a challenge, despite the clear necessity of understanding the impact of the timing of exposure (see Patz et al. 2014; Phalkey et al., 2015).

3. Foundational perspectives from public health and sociology

3.1. Exposure

In Epidemiology and Environmental Health Sciences, "exposure" is understood as the interaction between intensity, frequency and duration (Thomas, 1988; Berry et al., 1979; see also Carleton and Hsiang, 2016). Identifying exposure requires mapping an individual's history in terms of where (their location) they were and when (calendar timing) they were there. Research questions that investigate changes in health outcomes with attention to changes in exposure processes -where intensity, frequency and duration are allowed to vary – may yield insight into the linkages between exposure and adverse health. But this insight

[1] Direct linkages, such as heat waves and drought, create biophysical stress leading to adverse health outcomes (Huang et al., 2010; Kent et al., 2014, Grace et al. 2015). Indirect linkages also cause adverse outcomes but operate through more distal causes such as disease and inadequate nutrition (Grace et al. 2012; Brown et al., 2014; Grace, 2017).



Note: The time scale can represent months or years (see Greenland 1987)

Fig. 1. Five distinct and comprehensive patterns of exposure. Note: The time scale can represent months or years (see Greenland, 1987 for more information on exposure patterns).

may fall short of helping us develop useful and efficient interventions to protect those at risk of exposure unless scholars and policymakers specify and operationalize exposure in deliberate and consistent ways. Considering variation in the three components (intensity, frequency, and duration) alone would not allow us to identify and distinguish between climate change, climate shock and weather variability, for example. In other words, different types of climatic or weather-related exposures require notably different modeling approaches and have important implications for individual health outcomes and for policy- or public health-relevant interventions. The exposure models in Fig. 1 demonstrate these differences (see also NRC 2012).

While this approach to exposure-modeling is foundational in Environmental Health Sciences and Toxicology and used to guide investigations of health effects of chemical pollutants and cancer research in particular, it is not widely known or applied in health geography or in population-environment and spatial demography research.

The descriptions of the five different types follow. To aid in linking these exposure models to population health outcomes, brief examples of applications of direct and indirect linkages related to weather and climate are also provided within each description.

Type 1 – Continuous: The continuous pattern of exposure is useful to describe a static climate or weather experience that could lead to adverse health outcomes.

Examples: An example of direct linkages between population health and environment is continually high temperatures. In places where the temperature is always (or nearly always) above a temperature threshold, possibly indicating heat stress, then this model could be useful to compare over space or time how health outcomes relate to long term exposures to high temperatures. In terms of indirect linkages, we could consider malarious conditions. In communities where the weather/climate are always (or nearly always) suited to the survival of malaria causing parasites and vectors (as measured by temperature and rainfall conditions, for example), this model of continuous exposure is appropriate. A research design based on this exposure model would be relevant for researchers interested in investigating the health outcomes of individuals who live in warm/dry areas of a country versus those who live in wet areas of a country using different linking mechanisms. Certain weather-related events, such as flooding or drought, do not fit into this exposure type because these events are defined by a strong deviation from usual conditions.

Type 2 - Cyclic: The cyclic model of exposure describes repeated events that individuals are able to anticipate.

Examples: In relation to weather and climate, seasonal patterns can be referred to as cyclic. Direct linkages could then refer to “normal” seasonal temperature shifts like elevated temperatures during the summer hot season. While indirect linkages could refer to the typical disease (malaria or influenza, for example) season in communities where there is a clear beginning and ending to a disease season. Researchers interested in investigating the seasonality of biological and behavioral responses could base their research design on this model to examine the specific effects of temperature, net of seasonal norms.

Type 3 - Intermittent: The intermittent model of exposure refers to climate or weather events that occur irregularly but not necessarily infrequently.

Examples: In terms of direct relation to climate or weather events, we can consider a series of extremely cold (or hot) days during the normal cold (or hot) season as an example of an intermittent exposure. Extremes could be defined by either thresholds based on some biological/physiological knowledge or in reference to long-term norms, depending on the research focus. Indirect linkages could be used to investigate reduced agricultural production (in rainfed agricultural communities) as a result of a highly variable or late starting rainy season. Research focused on investigating the impacts of a seasonal heat-wave or food insecurity would base their research design on this exposure model.

Type 4 – Concentrated: The concentrated exposure pattern reflects a major event or climate shock that impacts many communities and may result in a recovery of extended duration.

Examples: A major drought, hurricane, fire or climate/weather related disease outbreak that results in major losses to agriculture, food systems and shifts in human interaction could be considered as a concentrated event that has both direct and indirect linkages to climate or weather. We consider these as cataclysmic events like the 1984/1985 drought in sub-Saharan Africa, the 2004 Indian Ocean earthquake and tsunami, hurricane Katrina in 2005 in New Orleans, or the 2018 European heatwave. Immediate health effects are experienced by those directly impacted by the event and health effects may be observed for many years after.

Type 5 – Unanticipated: The unanticipated exposure pattern refers to seemingly random and extreme events. In terms of weather and climate exposures, we can consider these events as sequential local "shocks".

Examples: Rainfall extremes like flooding or even longer-term seasonal events like virtually no rain during the rainy season for back to back seasons, can be incorporated into population-environment analyses using the unanticipated pattern of exposure. Indirect measures of random climate or weather events include flooding, crop disease or pest infestation – all of which are dependent on climate and weather but may occur seemingly at random and without any ability to predict (as opposed to cyclic exposures). The direct and indirect health effects of this exposure model may mirror those in types 3 and 4.

A perspective based on these exposure types incorporates the embeddedness of an experience. For example, the response to a major flood - as measured from quantitative topographic and rainfall data - will be very different in communities who have been routinely exposed to floods and have developed resources to cope with flooding from communities that are not routinely exposed to floods. However, the possibility that too many major floods or floods that occur too close in time can actually tax the community resources and cause the community to suffer in new ways must also be considered. Repeat floods in a community accustomed to floods can be modeled as either exposure type 2, 3, or 5 – depending on the specific timing and intensity of the flood.

These patterns of exposure are critical to consider when designing the research strategy and when deriving indices of environmental covariates to capture the complexity of the environmental factors of interest. Identifying which pattern characterizes the research setting and research goals allows analysts to make explicit, consistent, and correct underlying assumptions on which the analysis is based. Considering the exposure type also ensures that research questions and measurement are aligned, which leads to greater precision and accuracy in estimates and clarity in results and interpretation.

3.2. Geographical context

It is important to consider spatial context to best understand and model environmental norms and deviations. For example, specific types of seasons vary according to local environmental conditions and the resulting cultural and economic responses. In low income countries, seasonal changes are associated with weather patterns but also with food security. The Famine Early Warning System Network (FEWS NET) has developed country-specific calendars that identify specific seasons of relevance for early warning systems, like the hunger season (see fews.net). While the general timing of the hunger season is consistent year to year, within-year variability in rainfall can have major implications for the length or the severity of the hunger season in a given year and in a given community (see, for example, Eggen et al., 2019). In high income countries, spatially varying seasonal patterns of influenza or temperatures, for example, are also relevant and require consideration when developing a research approach (Dorélien, 2019; Isen et al., 2017; Wu et al., 2019). Considering exposure conditions with relation to local or community environmental and social norms, histories, and mitigation strategies is fundamental to developing place-based analyses of exposure.

3.3. Life course theory

Exposure models provide guidance on how to differentiate between exposure types, but they do not directly correspond to demographic or health-related events. Life course theory provides a vital tool for explicitly identifying the exposure process of interest to the analyst. Through considering each individual's unique life experiences with regard to the exposure models, researchers can clearly specify the process of interest to their study.

The life course is a concept widely used in Sociology, Demography and Epidemiology, where age-differentiated experiences occur as a sequence of events. Life course theory embeds these sequences in a particular space and time (Elder, 1977, 1994). The development of individuals is shaped, constrained and fostered by the conditions that surround them. Huinink and Kohli characterize the life course as a "system of interdependent dynamics that unfolds over time" (Huinink and Kohli, 2014: 1293). A fundamental idea in life course research is that what has happened in the past is relevant to the present situation. Circumstances experienced can be envisioned as having a ripple effect, chain reaction or reverberations (Mitchell, 2003). In this way, an individual's health and well-being is influenced by present as well as past conditions. This perspective therefore naturally encompasses geographical and sociohistorical influences on individual's behavior and experiences.

If we know that past conditions are influential, we can keep history in mind at the most basic level by assessing whether individuals lived through a particular time period in a location where there was a particular exposure. This focus can be useful when analyzing topics as wide ranging as the effect of an earthquake to the effect of experiencing the death of a loved one. Individuals may have many shocks or influential life experiences. The life course approach advocates accounting for advantages and disadvantages of past circumstances that accumulate over time. The social and economic disruption caused by an earthquake at the macro level can be compounded by repeated events, just as the individual loss accompanying deaths in the family.

Most specific to the life course approach is the emphasis on the intersection of personal biographies and factors specific to a particular place and time (Elder, 1985). This implies that *when* individuals are exposed to certain influences is also relevant to consider. We might think of this as the intersection of two clocks: an individual's time and calendar time. Epidemiologists discuss this aspect in terms of critical or sensitive periods (Kuh and Ben Shlomo, 2002, 2004), where a critical period is the only length of time during which a circumstance has an effect on individual's development or outcomes and a sensitive period is when an effect is particularly strong. The outcomes related to exposure during critical and sensitive periods may appear years after the exposure. To use an earlier example, the death of a parent may have particularly detrimental effects on life expectancy if this event occurred when an individual was a young child (Rostila and Saarela, 2011).

Life course theory points to the necessity of mapping how absolute and relative timing and exposure matters to an outcome. A complete accounting of exposure therefore includes both accumulation and relative timing, which are regularly missing from population-environment research.

4. Using a life course approach to update and frame models of environmental exposure

Integrating life course theory with the five distinct exposure processes provides a cross-disciplinary organizing framework useful for thinking about human-environment interaction that then supports the specific demands of a given research question and available data. Spatial and temporal variation are required for rigorous research on population health and environment relationships, as demonstrated in demographic and geographical research, but the spatial and temporal scale will vary depending on the research goal. For example, a climate shock as depicted in type 4 might be a flood that occurs at one point in time with after effects felt in one community for several months and in another, nearby community for a shorter time period. These processes are therefore operationalized using place and time specific metrics corresponding to the spatial or temporal scale of interest.

We synthesize and summarize a general approach to considering each exposure type integrated with the life course. As relevant, we relate back to some of the current trends in population-environment research that do not explicitly identify the exposure process of interest.

Type 1, Continuous: Instead of quantitatively measuring some degree of deviation from the long-term climate norm without explicitly stating the mechanism under investigation, clarify if the goal is to investigate health differences between those acclimated to certain climate conditions versus other climate conditions. Acclimation should be defined based on the specific period of interest in the life course: for example, comparing those who were exposed to chronically high temperatures during adolescence to those who were exposed to moderately high and cool temperatures. Another way of considering the role of the life course is to consider the events of an individuals' life that may help or inhibit an individual's ability to cope or recover from an event.

Type 2, Cyclic: In regression analysis, calendar month fixed effects or fixed effects for specific seasons (growing season, malaria season) have been used to capture exposure to cyclic environmental factors. Sometimes this approach is referred to as “adjusting for seasonality” where the goal is to account for the variability in the outcome variable taking into account the average response to a seasonal trend. With attention to life course, normal seasonal conditions can be mapped onto individual's lived experiences, age development and critical or sensitive periods to help investigate the role of consistent, repeated, and anticipated exposures.

Type 3, Intermittent: An important distinction here from cyclic, is that intermittent models represent a within-season analysis and so require fine-temporal scale detail. A seasonal/annual temperature or rainfall average would likely not capture these finer scale variations. In other words, we are not simply investigating effects of the hot season, but a heat-wave during the hot season. Using this exposure model, it is vital to consider the linking mechanism of interest to the outcome because the construction of the variable will change depending on if the focus is about perceptions of vulnerability (the rainy season started late so a household will store food in preparation for a potentially poor harvest) versus experienced outcomes (a heat-wave during the hot season), for example. Fine-temporal scale detail of individuals' life course stage also improves an analysis of intermittent exposure; being able to locate a heat wave during a particular trimester, for instance, will improve the precision of estimates in assessing how heat may be related to pregnancy outcomes.

Type 4, Concentrated: Specific location of a weather or climate “shock” on a fine temporal and spatial scale is also required for this type. Incorporating the life course perspective requires consideration of how the timing and sequencing of the event in the life of an individual might have been related to other events. For example, if a climate shock like a hurricane impacts conceptions the timing of the first birth may also be impacted. Important to also consider are the ways that a climate shock would impact conceptions: through a reduction in access to contraception for some couples, through biological linkages related to psychological stress that inhibit ovulation or through behavioral linkages related to the frequency of sexual activity.

Different types of concentrated events may also occur at different key periods in the life-course with impacts that vary based on previous exposures to other extreme events. Individuals who have faced repeated extreme events – a severe drought during pregnancy, followed by exposure to an earthquake during early childhood, for example – may face unique challenges that come with the compounding effect of exposure to concentrated events. Each of these mechanisms will also have a spatial component that must also be considered. Although analyses are often aimed at understanding the effect of one factor, such as rainfall, on an outcome, the combined effect of other distinct factors such as natural disasters can be modeled and is important to consider to get a full picture of maternal, reproductive and child health.

Type 5, Unanticipated: Unanticipated events require attention to the local history and context and can be well incorporated into life course studies because of the focus on the ways that unanticipated events happen over time. For example, using the hurricane example from Type 4 above, an unanticipated and extreme hurricane may have long lasting effects on contraceptive use because of major impacts on access to health resources and contraception. Depending on the human health linkage under investigation, the impacts of unanticipated events can naturally work through either direct (psychological stress resulting from repeated exposure to extreme unanticipated events) or indirect (reduction in available household resources) ways and will impact health outcomes differently, depending on the individual's unique experiences and conditions.

It is also important to note that sociological perspectives suggest that individual vulnerability and resilience is heavily impacted by individual-, household-, and community-level norms and resources (Spini et al., 2017; VanLandingham, 2017; Fussell et al., 2010). In other words, individual factors related to education, socio-economic status, race, religion or ethnicity will also shape outcomes, even after considering the interaction between the environmental exposures and the individual life course. Extreme weather events, like floods or droughts, will also have different population and health impacts depending on the demographic characteristics of a community and the social, historical, economic and political conditions (Brown et al., 2015; Brown and Funk, 2008). The time it takes for a heat wave or drought, for example, to induce a food system failure depends on community characteristics related to climatic/seasonal norms, agricultural practice and broader food system conditions (Niles and Mueller, 2016; Morton, 2007). In terms of diseases like malaria, considering spatially varying measures of endemicity are vital for determining the risks associated with malaria exposure. It is therefore typical practice to approach this type of analysis with a focus on variation between-individuals versus within-individual and between-community versus within-community to account for spatial variability in the relationship but also to investigate how individual health outcomes vary within specific contexts (Grace et al., 2016; Balk et al., 2005, de Sherbinin, 2011; Shively, 2017, Shively et al., 2015).

5. Applications to MRCH research

Currently, the importance of environmental exposures for short-term and later-term adverse health and economic outcomes is rapidly gaining importance in policy and health research. Understanding the ways these specific drivers impact MRCH outcomes is critical in light of evidence that climate change will increase rainfall and temperature variability and extremes across the planet, adversely affecting the health of millions (Hertel, 2016). While research has uncovered large effects on pregnancy and early life health outcomes of exposure to

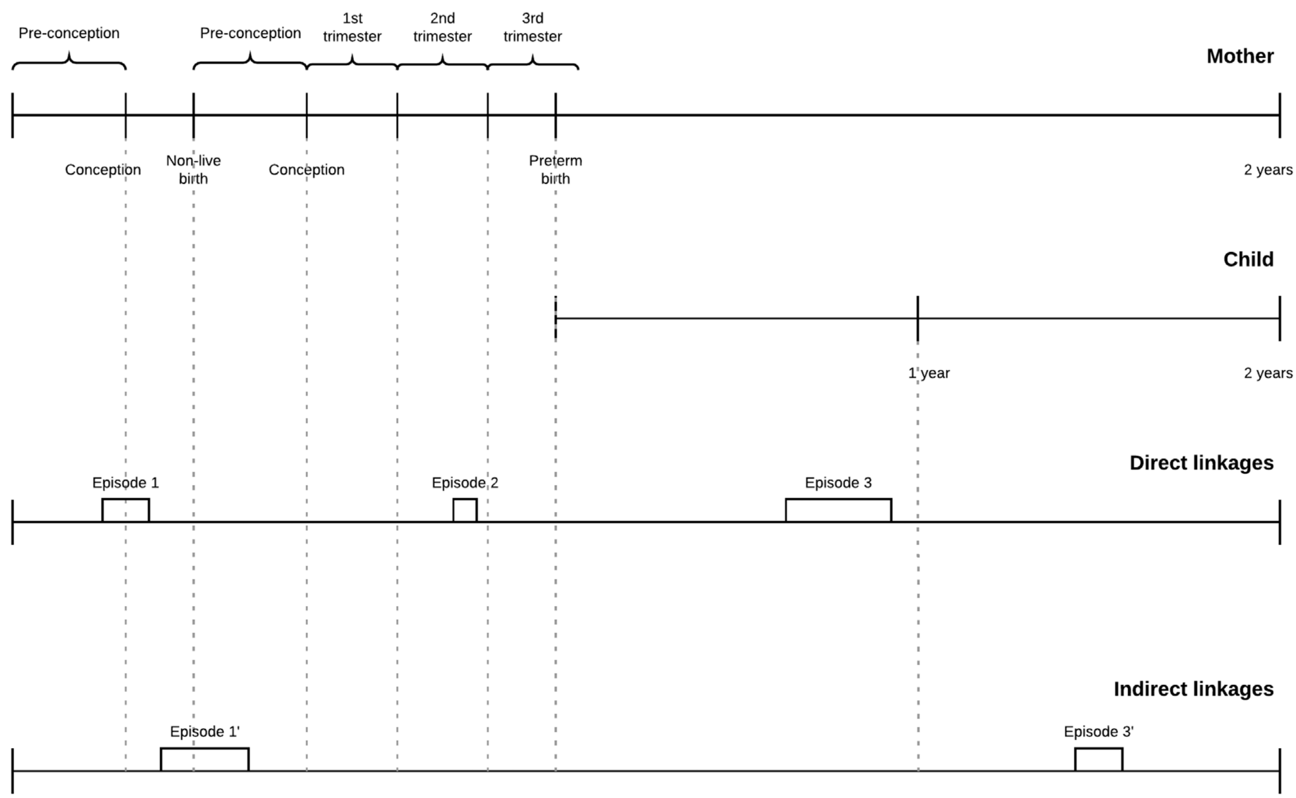


Fig. 2. Temporal and geographic linkages between climate or weather exposures and MRCH outcomes. Note: The Mother and Child timelines depict events (conception, non-live birth, live birth) and periods (pre-conception, trimesters of a pregnancy, first year of a child's life) during their life courses. The Direct Linkage timeline depicts events (flood, hurricane, other extreme weather event) or periods (drought) that have direct impacts on MRCH outcomes. The Indirect Linkage timeline depicts events or periods caused by direct linkages that have indirect impacts on MRCH outcomes. For example, Episode 1 on the Direct Linkage timeline is a drought that then causes reduced food production in Episode 1 on the Indirect Linkage timeline. As evident in this example, the reduced food production appears to make it difficult for the Mother to get adequate nutrition, causing fetal stress, and ultimately, a non-live birth event.

weather- or climate-related events, like heat waves or malaria, there has been limited work examining the timing of exposures, the accumulation of exposure, the impact of different exposure types/durations, the reversibility of and sensitivity to exposures, and geographic disparities in exposure with respect to pregnancy, birth, and early childhood outcomes. This research is limited in rich, poor and middle-income countries alike because data on pregnancy outcomes and exposure to climate events or climate characteristics is not consistently collected. Poor women and children in poor countries may be particularly important to study both because of a high-level of dependence on rainfed agricultural systems for their livelihoods and they may face a double burden of climate change through exposure to both direct and indirect pathways linking climate to health outcomes (see, for example, Grace et al., 2017; Isen et al., 2017; Kudamatsu et al., 2012; Strand et al., 2011; Basu et al., 2016).

For the purposes of illustrating the information described in the previous section focused on updating existing approaches, while also considering the conceptual framework as stated in the previous paragraph, we develop Fig. 2. In Fig. 2 we conceptualize the temporal and geographic linkages between climate and weather exposure and MRCH health outcomes by using time-lines for women and children. Contained within MRCH outcomes, such as birth weight, is both the reproductive life course relative to the woman and early childhood life course events relative to the long-term health and development of an infant or child. Women of reproductive age experience many stages of the reproductive life course that are potentially influenced by environmental exposure, including pre-conception, conception, pregnancy, non-live births, live births, and post-partum.

For example, the woman depicted in Fig. 2 experiences X years (or months) before becoming pregnant. She is then pregnant until she experiences a non-live birth (e.g., spontaneous, induced abortion or stillbirth) or a live birth (low birth weight or healthy birth weight). After a non-live or live birth, the woman transitions back to a pre-conception status until experiencing menopause.

For child-centered analyses, children are born during a live birth, are infants for one year (when they are particularly vulnerable to disease, food insecurity, and heat stress), breastfeed generally for up to 24 months, and then transition to childhood. The circumstances or conditions relating to their mother's reproductive life course or factors related to pregnancy and early infancy have the potential for long term health and development impacts for the child as they age into adulthood (Isen et al., 2017; Wilde et al., 2017).

Referring back to the updated framework, we can establish the mechanisms of focus to identify the climate exposures in different ways with health outcomes reported in spatially referenced survey data (the Demographic and Health Surveys (DHS), for example) to quantify linkages. All surveyed women with retrospective reproductive life course information and geospatial data associated with their place of residence *at the time of the event or over the period of time of interest,* can be matched to a graphic like the one above but that is specific to their own lived experiences. The graphic is important because it illustrates the different time frames associated with direct climate exposures like heatwaves or droughts versus indirect climate exposures like food insecurity.

We can then consider the five types of exposure and the ways that each exposure type impacts the pregnancy, the woman, or the fetus/infant. Each exposure type may impact MRCH outcomes in different ways and will relate to the standard conceptual framework employing determinants related to biology, behavior, nutrition or socio-environmental characteristics. An analyst may then sort out the population of exposed women and/or infants (or pregnancies) that correspond to different climate events of interest. For example, if there was a major and unanticipated quick onset climate event (like a typhoon (Type 5)), how would aspects of the standard conceptual framework be impacted and can we consider these impacts with respect to an individual's current reproductive life stage. Employing this approach facilitates investigations that differentiate between the impact of multiple exposures on a single person or community and the geographic disparities in MRCH outcomes according to one widespread shock.

Similarly, repeated events like a standard annual "hunger season" resulting in a seasonal food shortage, may have direct impacts on biology (impacting fecundity or fetal growth) that might impact the short- and long-term reproductive outcomes of pregnant women or their fetuses/infants. However, these health impacts will be conditioned by past reproductive histories and past experiences coping and preparing for anticipated events (Type 2). Two women may live in the same community and face nearly identical climate conditions during a given period of time, but their biological and behavioral responses may differ widely depending on their personal reproductive life course stage as well as their unique experiences coping with similar conditions over their lifetime. In other words, some individuals may acculturate (biologically) to specific conditions or develop strategies to ration food or secure community support (behavioral). Explicitly merging the individual history of exposures with life course theory, and considerations of the actual environmental event of interest organizes research approaches and mechanisms so that the scholarly and policy community can better specify hypotheses and research outcomes.

In each of these exposure types, it is also important to consider the potential impacts of migration on data collection and determining exposure histories. While some smaller surveys include detailed migration histories, the vast majority of large-scale health surveys include very little information on where people have lived, despite the potential for weather or climate events to displace individuals. In practice, surveys may be collected in a community where an individual has spent very little time and, without attention to length of time in the community, result in exposure misclassification. While exposure misclassification is likely to bias results towards the null (Jurek et al., 2005; Zeger et al., 2000), the complex linkages between migration, climate, and health must be addressed in the design of the analysis and be considered in the interpretation of the results. For example, Demographic and Health Surveys (DHS) have often included a question such as "How long have you been living continuously in (NAME OF CURRENT CITY, TOWN OR VILLAGE OF RESIDENCE)?" Best practice in sample selection would then limit the individual exposures in the past to only those at the current and known location. This consideration can result in selection bias because the analysis then only includes those who have not moved due to particularly negative exposures (such as conflict or drought). Analysts can, however, assess how different the outcome patterns are across individuals who have migrated to another area (length of time in residence is shorter than others) and those who have not and draw conclusions about the generalizability (e.g., Lindskog, 2016).

6. Conclusion

Interdisciplinary population-environment research is fraught with challenges and inconsistencies in results. Merging data of different types and with different spatial and temporal scales poses a range of technical, conceptual, statistical, and disciplinary challenges. However, because there are many potential insights to be gained from combining different types of data, we believe that these are worthwhile efforts. To support scholars developing interdisciplinary population-environment research, we aimed to develop a framework that can be used to guide foundational challenges related to data aggregation and data application. A wide range of approaches are used to investigate quantitative population health questions that incorporate climate or environmental details. Often the authors provide limited detail on why they approach the research in the way that they do, nor do they specify the underlying mechanism that they are trying to identify. The result is a series of related analyses and projects without clear interpretation. The purpose of this paper was to first bring attention to the problem of the lack of consistency in approaches to environment-population research. The second aim of this project was to explicitly outline a framework for moving related research forward that organizes exposures and climate events into distinct categories and embeds them into the life course.

As with other scholars who have encouraged the development and use of a theoretical framework to provide a common language and approach to addressing contemporary and pressing public health issues (Victora et al. 1997; Carleton and Hsiang, 2016), we argue that the framework proposed here should guide the research from a project's early development and can be used to support and inform data aggregation approaches that are necessary when merging data with such different characteristics. Research that pulls from multiple disciplines, as population-environment research does, requires careful consideration of mechanisms. Explicit and clear use of frameworks facilitates access to this research across broad groups of academics (quantitative and qualitative), policy makers and activist or community groups. Clearly describing why and how a researcher approaches and models the link between an environmental exposure and a health outcome will facilitate development of mitigation policies at different scales.

Considering both the place and the individual in the place dramatically shifts the ways that we design research. Incorporating measures of long-term temperature or rainfall norms is a relatively common approach to accounting for climate change or climate norms in a given community, however, unless we consider (and engage with local communities) the actual lived experiences of the people in the communities – we could be inappropriately attributing individuals with experiences and exposures. Linking exposure types and timing to the reproductive life course in the ways that we have highlighted here allows us to explore complex interrelationships between the environment and health outcomes in new and innovative ways. Importantly, in identifying the exact exposure process (one of the five exposure types), the critical period of interest in the life course, and explicitly considering the mechanism (direct or indirect) that links the environmental context to individual MRCH outcomes, this integrated approach can help ensure that social science scholars and analysts are creating a common ground in approaching human-environment research.

Author contributions

Authors 1 and 2 conceptualized the project with feedback from author 3. Author 1 developed the original draft of most sections of the paper based on detailed conversations with authors 2 and 3. Author 2 developed the original text for the "lifecourse" section of the paper. Subsequent drafts were edited by all three authors. Writing and editing the revised document was primarily the responsibility of authors 1 and 2. Author 3 constructed the graphics based on conversations with author 1.

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