The stability of peri-urban croplands globally: An approach to examine exposure to climate extremes

By

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Table of contents

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List of tables

List of figures

Abstract

Croplands are subject to a variety of pressures, including the influence of urban expansion on cropland area and the impacts of climate change on crop yield. As the world's population becomes increasingly urbanized, there is a growing need to understand the relationship between urban areas and the surrounding 'peri-urban' croplands in their hinterlands. However, global-scale analyses face a challenge of inconsistencies in the boundaries to assess peri-urban croplands and thus local food production. My thesis addresses this gap by applying a consistent travel-time-based approach and a high-resolution global cropland map to delineate the peri-urban cropland catchment of 2,425 urban centres with populations greater than 250,000 worldwide. I then calculated the stability of cropland over a 16-year period between 2000 to 2019 within these catchments, which revealed sharp geographic differences among urban centres in terms of their peri-urban cropland change dynamics. Applying these catchment boundaries, I then present a procedure that can be used to determine crop-specific exposure to extreme heat in these peri-urban croplands. Current studies of cropland's exposure to extreme temperatures tend to focus on regional and continental trends, with less emphasis on local agriculture specific to individual cities. Specifically, I describe a subset of urban areas (n=929) with a minimum cropland area of 10% within their catchments alongside a condition that 80% of that cropland was stable between 2000–2003 and 2016–2019. My proposed approach provides a heuristic that can be applied for specific urban areas globally to help guide land-use planning and climate-adaptation measures to support peri-urban crop production. To identify gaps in the global food system with global urbanization, we need to improve our understanding of where peri-urban croplands are located, how they are changing, and how climate change may impact them.

Introduction

In a rapidly evolving world, we must constantly seek to improve our understanding of how human activity is changing the land—particularly in the case of agriculture and the food system. The world's populations continue to urbanize, with two-thirds of all people expected to live in a city by 2050 (United Nations 2019). This growth and the associated increase in urban land area has often and will likely come at the expense of the 'peri-urban' croplands located on the outskirts of cities (Li, Verburg, and van Vliet 2022; Shaw, Vliet, and Verburg 2020). Alongside changes in cropland area that could affect food production, there is a compounding effect due to climate change, such as the increase in mean temperatures and exposure to extremes that can impact crop yields (Karger et al. 2023). These global changes in temperatures have already begun to have a meaningful impact on the production of key crops by pushing them beyond their physiological limits, which is expected to further increase this century (Ray et al. 2015, 2019; Lobell, Schlenker, and Costa-Roberts 2011; Jägermeyr, Müller, Ruane, et al. 2021). Taken in sum, the loss of peri-urban land used for agriculture and the impacts of climate change on crop yield represents a significant threat to the global food system and a need to understand where and how these shifts will occur.

Considering croplands from an urban perspective

Much of the world's croplands are located near urban areas, with 60% of all irrigated cropland and 35% of rain-fed cropland within 20 km of a city in 2000 (Thebo, Drechsel, and Lambin 2014). While local agriculture is not typically sufficient to support the full dietary demand of a city, nearby agriculture serves as a meaningful source of key food staples (Kinnunen et al. 2020; Schreiber et al. 2021). However, croplands located around cities can face significant pressures due to urban expansion. In addition to a growing global urban population, built-up land area has been expanding rapidly to support this growth in some regions (Li, Verburg, and van Vliet 2022). This poses a potential threat to peri-urban croplands, which have often been converted to support urban expansion (Shaw, Vliet, and Verburg 2020; Potapov et al. 2022). With their high yields and geographic proximity, the loss of these croplands could undermine the resilience of urban food systems (Nelson et al. 2021; Béné et al. 2016; Seekell et al. 2017). While serving as consumers of nearby agriculture, urban areas directly influence their peri-urban regions through their policy decisions and their contributions to higher temperatures (Shaw, Vliet, and Verburg 2020; Tuholske et al. 2021). Considering the deep interconnections that cities have with their hinterlands, municipal policies and planning must be central in any discussion of local agriculture; they serve as a key determinant of the success of peri-urban food production (Schreiber et al. 2023).

The foodshed and its relevance to urban centres

When discussing a city's local food system, the simplest approach is to consider its 'foodshed'. A foodshed is the agricultural catchment of a population centre that can exist at the local, regional, and global scales (Kinnunen et al. 2020). The concept of a foodshed has tended to follow one of two definitions in the literature, as described by Schreiber et al. (2021), with some studies identifying a foodshed as "the *actual* geographic areas from which a population sources its food" while others treat a foodshed as "any area with the *potential* to feed a given population" (Original discussion by Peters et al. 2009). This is a crucial distinction: studies attempting to model foodsheds require abstractions based on the production capacity and consumption of an area, which can entail considering agricultural trade and complex food flows (Karg et al. 2023). At the global scale, this can be seen in Kinnunen et al. (2020), who define a foodshed as "areas linked together through movement and consumption of food," though their study relies on modelled agricultural trade flows and thus falls into Schreiber et al.'s (2021) definition of the *potential* food sourcing regions. The application of a foodshed also can be seen in studies that do not use the term. For example, Nelson et al.'s (2021) assessment of the resilience of international and domestic agricultural trade networks echoes the foodshed concept through its focus on the inherent spatial links within and between nations. Modelling these inter- and intra-national agricultural networks to determine global foodsheds is a complex and resource-intensive task, with current leading efforts requiring complicated methodologies and assumptions while remaining fairly coarse-grained (Kinnunen et al. 2020; Nelson et al. 2021).

Due to the difficulty of determining the real-world foodshed of a city and the complexity of undertaking a global approach to foodsheds, I chose to focus on examining croplands at the peri-urban scale, which could be thought of as part of an idealized local foodshed (Peters et al. 2009). While my hypothesis is that local peri-urban crop production is likely insufficient to support the demands of most urban areas for some crops (such as grains and a wide array of fruits), it could play a more pivotal role in providing certain crops, such as pulses, roots, and other vegetables[1]. Considering the myriad impacts that cities can have on their peri-urban regions, it is pivotal to address each urban area individually to facilitate each area's actions to benefit nearby agriculture.

[1] In their global analysis of foodsheds, Kinnunen et al. (2020) indicate that pulses, cereals, and rice had the highest rates of potential local fulfillment of their studied crops (22–28%), while tropical roots and maize had much lower local fulfillment potentials (11–16%).

Examining the impacts of climate change on local crop production

It is well established that global temperatures have been rising and will continue to do so, which will have a host of impacts on agriculture globally (Heino et al. 2023; Jackson et al. 2021; Zhu and Troy 2018; Jägermeyr, Müller, Ruane, et al. 2021). However, there are important nuances to consider. An area's terrain can have a notable impact on its climate and can moderate increases in temperature (Karger et al. 2023). While studies have investigated the exposure of urban areas to temperature extremes and others have examined rural agriculture's exposure to extreme temperatures, no studies have tackled both (Mueller et al. 2016; Tuholske et al. 2021). We could therefore expect that peri-urban croplands would be subject to a unique climatic exposure. This, to my knowledge, has not been fully studied (especially at the global scale).

Several methods have been used to determine cropland's exposure to extreme temperatures. Due to variation in their distribution and physiology, different crops can have vastly different tolerance for extreme temperatures that continue to evolve with changing temperatures (Butler and Huybers 2013; Jackson et al. 2021; Song et al. 2022). In particular, when crops are exposed to extreme temperatures during their growing period, they degrade rapidly in a non-linear trend (Schlenker and Roberts 2009; Butler and Huybers 2013). This results in a conundrum for croplands near cities, as they are subject to similar heat exposures as urban areas, but have a greater proportion of evapotranspirative cooling (Findell et al. 2017). Many studies tackle this by establishing a threshold temperature, above which a crop's yield begins to suffer. In practice, this means identifying any daily maximum temperature that exceeds a threshold as a Killing Degree Day, or KDD (Jackson et al. 2021; Zhu and Troy 2018). However, this requires establishing a threshold for every crop considered, which is difficult and uncertain (Song et al. 2023; Butler and Huybers 2013). For example, in their analysis of cropland intensification and centennial trends in the summer climate of the U.S. Midwest, Mueller et al. (2016) identified the 95th percentile of daily maximum summer temperatures (June-August) that crops are exposed to; however, while relatively simple and consistent, this is an innately comparative approach.

Objectives and research questions

In this thesis, my primary goal was to evaluate the exposure of peri-urban croplands to extreme temperatures. However, this required a first step to assess city-specific peri-urban cropland areas (local foodsheds) and their stability over time, leading me to the travel-time-based approach to determining the influence of an urban area pioneered by Cattaneo, Nelson, and McMenomy (2021). Because their study focused on the 'urban-rural continuum' more generally (a classification irrespective of any single city), rather than the catchments of individual cities, this led me to generate my own peri-urban foodshed catchments for 2,425 individual urban centres. Additionally, due to the pioneering work of Weiss et al. (2020), these catchments were modern (representative of 2019), but it is unreasonable to assume that these catchments (and the croplands within them) have remained in the same location and extents for the full duration of a climate-centred analysis. To address this concern, I calculated the stability of cropland within these peri-urban foodsheds, which offers a novel perspective into the changing food systems in many regions. While my primary focus on assessing the extreme temperature exposures was stymied by processing limitations, I propose a heuristic to complete such an anlaysis in the future.

Methods

My thesis proceeded in three major steps: the generation of the travel-time based foodsheds, assessing the stability of cropland within these foodsheds, and comparing each foodshed's exposure to extreme heat. The foodsheds were generated at the 60-, 180-, and 300-minute ranges for each individual urban centre present in the Global Human Settlement Layer Degrees of Urbanization dataset (Schiavina, Melchiorri, and Pesaresi 2023). Then, using temporal cropland data for 2000–2003 and 2016–2019, I calculated the total cropland within each foodshed and the amount of stable cropland[2]. To ensure that agriculture within the foodsheds were stable for the extent of the extreme temperature analysis, a filter for a total cropland amount of $\geq 10\%$ and a stable cropland amount of $\geq 80\%$ was applied. I then establish an approach for determining the crop-specific exposure to extreme heat for each selected foodshed.

Input Data

Name	Method	Time Period	Spatial Scale	CRS	Usage	Source
GHS-SMOD	Foodshed generation	2020	1 km	World Mollweide, EPSG:54009	Urban centre identification	Schiavina, Melchiorri, and Pesaresi (2023)

[2]As I later define, stable cropland is cropland that occurs in the same place in both epochs (i.e. present in 2000–2003 and 2016–2019).

Name	Method	Time Period	Spatial Scale	CRS	Usage	Source
GHS-POP	Foodshed generation	2020	1 km	World Mollweide, EPSG:54009	Population filtering	Schiavina et al. (2023)
GHS-UCDB	Foodshed generation	2015	1 km[3]	WGS 84 (EPSG:4326)	Population filtering and settlement names	Florczyk et al. (2019)
Global Motorized Friction Surface	Foodshed generation	2019	30 arc seconds (~0.92 km @ equator)	WGS 84 (EPSG:4326)	Accessibility surface generation	Weiss et al. (2020)
Potapov Cropland	Cropland stability	2000–2003 and 2016–2019	0.9 arc seconds (~30 m @ equator)	WGS 84 (EPSG:4326)	Crop-agnostic cropland area	Potapov et al. (2022)
MIRCA2000	Crop-specific extreme temperature exposure	2000	5 arc minutes (~9.2 km @ equator)	WGS 84 (EPSG:4326)	Crop-specific and irrigation method-specific harvested areas	Portmann, Siebert, and Döll (2010)
GGCMI Phase 3 crop calendar	Crop-specific extreme temperature exposure	?	30 arc minutes (~55.6 km @ equator)	WGS 84 (EPSG:4326)	Crop-specific and irrigation method-specific crop calendars	Jägermeyr, Müller, Minoli, et al. (2021)

[3] Though provided in a geographic coordinate system, the GHS-UCDB was generated from projected input data. Florczyk et al. (2019) provides its resolution as "1 km" for this reason.

Name	Method	Time Period	Spatial Scale	CRS	Usage	Source
CHELSA-W5E5	Crop-specific extreme temperature exposure	1986–2016[4]	30 arc seconds (~0.92 km @ equator)	WGS 84 (EPSG:4326)	Global daily max temperature values	Karger et al. (2023)

Table 1: Input data sources with their respective uses, temporal information, resolution, and coordinate reference system.

Travel-time-based foodshed generation

Determining the boundary of an urban centre

Due to its open-access, high-quality, and frequent use in the literature, I make use of the European Commission's Global Human Settlement Layer (GHSL) (Tuholske et al. 2021; Weiss et al. 2018; Nelson et al. 2019; Cattaneo, Nelson, and McMenomy 2021). This takes the form of the GHS-POP (population) layer for 2020, GHS-SMOD (Modeled Degree of Urbanization) layer for 2020, and GHS-UCDB (Urban Centre Database) layer for 2015 (Schiavina et al. 2023; Schiavina, Melchiorri, and Pesaresi 2023; Florczyk et al. 2019).

Using GHS-SMOD, -POP, and -UCDB, I identified each unique urban centre through an adaptation of the methodology established by Cattaneo, Nelson, and McMenomy (2021) (see Figure 1). The urban centres were identified in GHS-SMOD and associated with the population values in GHS-POP and GHS-UCDB, alongside the city and country names provided in GHS-UCDB. Points were then generated every 500m along the edge of the boundaries. As these steps were conducted at 1 km resolution and aligned to the same grid, the final step was to project the data into the same coordinate reference system as the friction surface used to generate the travel-time foodsheds (WGS 84, EPSG:4326).

Once both the urban centre polygons and points were generated, they were imported into R for further processing. There, I separated each urban centre's points to facilitate later processing. Though a population filter was initially considered, the base filter from GHSL-SMOD's urban centre classification of $\geq 250\,000$ was maintained.

[4] While CHELSA-W5E5 Version 1 covers 1979–2016, I selected 1986–2016 as a more relevant 30 year span of climate data due to its greater overlap with the rest of the selected data.

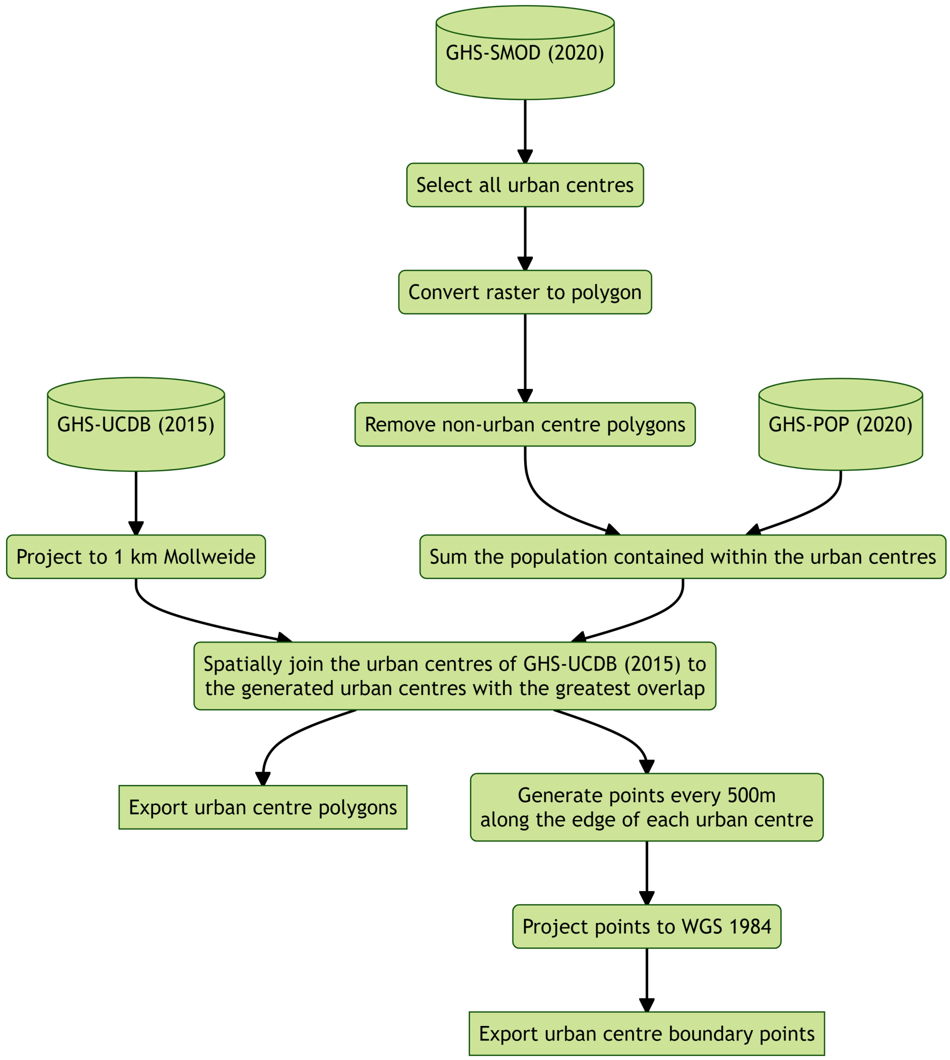


Figure 1: Workflow for generating the urban centre polygons and points that were used in Figure 2. This procedure was adapted from the work of Cattaneo, Nelson, and McMenomy (2021).

Generating travel-time catchments for each urban centre

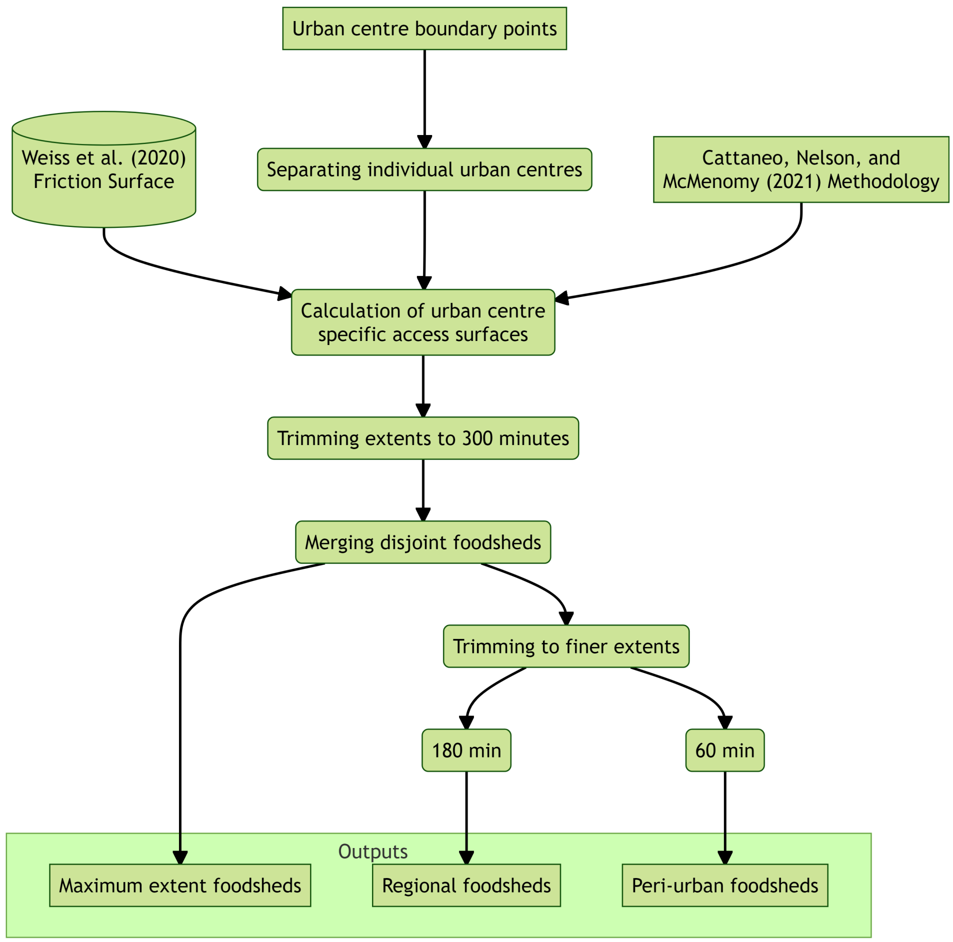


Figure 2: Workflow for generating the travel-time-based foodsheds.

After the separation step, the travel-time catchments were generated for each urban centre (Figure 2). These catchments are typically referred to as 'accessibility' surfaces, reflecting the time required to 'access' a location and constructed using a 'friction' surface which similarly reflects the cost (or 'friction') to move through the cell (Weiss et al. 2018). Using Weiss et al.'s (2020) Global Motorized Friction Surface's high resolution, modern, and global extent, it was possible to generate an accurate and location-specific representation of each urban centre's peri-urban foodshed. Drawing from the methodology established by Nelson et al. (2019)

and Cattaneo, Nelson, and McMenomy (2021) and van Etten's (2017) implementation of least-cost distance calculations for R, it was feasible to implement this approach in contrast to other methods used (such as distance-based fixed buffers).

After initially creating each travel-time surface, it was in its raw $5.5°^2$ extent. Though an arbitrary cutoff point, 300 minutes was selected as the maximum extent of each urban centre's catchment, with 180- and 60-minute catchments created to be more representative of their regional and peri-urban foodsheds, respectively. Due to ArcGIS Pro's default behaviour of using four-point contiguity (instead of eight-point contiguity[5]) when generating polygons from rasters, resulting in some urban centres appearing as separate entities. This was addressed by merging the travel-time surfaces for all of the separated pieces of the urban centres.

Cropland and urban stability

Crop-specific or crop-agnostic?

A necessary question as part of any study of agriculture's exposure to heat is crop specificity. Crop specificity offers considerable advantages by considering a specific threshold temperature that cause significant damage to a crop and a discussion of the impact on locally relevant food crops. However, there are major disadvantages to applying a temperature threshold. Acquiring high-resolution crop-specific datasets is a difficult feat, with even recent state-of-the-art crop-type masks containing information on only four major crops (Becker-Reshef et al. 2023). Older, well-regarded crop-specific data on crops' harvested area such as SPAM (Spatial Production Allocation Model, 2010), MIRCA2000 (2000), and EarthSTAT (2000) are both coarse (with 5 arc minute resolution) and aging (Yu et al. 2020; Portmann, Siebert, and Döll 2010; Monfreda, Ramankutty, and Foley 2008). Using these datasets would defy two of the main advantages of my travel-time local foodshed approach: its modernity (with local foodsheds representative of 2019) and its fine resolution (30 arc *seconds*).

A crop-agnostic approach focused solely on potential exposures of *cropland* to extreme temperatures addresses the issues of both age and resolution, with recent data from Potapov et al. (2022) identifying cropland in Landsat data from 2000 to 2019 at 0.9 arc second resolution. While this loses the potential for applying a KDD approach, crop-agnosticism can provide a more accurate representation of the temperatures to which all crops are exposed. While this paper ultimately opted for a crop-specific approach to extreme temperature exposure using MIRCA2000 due to its data on irrigation and use in relevant studies, this time-

[5] Otherwise referred to as rook contiguity and queen contiguity, respectively.

specific cropland data was used as a screening step to assess the stability of cropland for part of extreme temperature analysis.

Approach

To identify the stability of cropland for each urban centre, I used the global cropland data time series from Potapov et al. (2022). This dataset has a fine resolution (0.9 arc second, ~30m at the Equator) and identifies all cells that served as cropland in a series of four-year epochs (to account for cropland dynamics, such as loss and gain). As the travel-time surfaces are representative of 2019, the stability of cropland between 2000-2003 and 2016-2019 was used as a proxy to assess the stability of the travel-time catchment (e.g., no major urban expansion that would result in the loss of cropland in the 20-year period). This led to a series of screening steps for each catchment where the cropland data for both 2000-2003 and 2016-2019 were masked by the travel-time surface and then added together. This resulted in a raster with three values: 0, indicating that cropland was not present in either cropland epoch (**no** cropland); 1, that cropland was present in only one epoch (**unstable** cropland); or 2, that cropland was present in both epochs (**stable** cropland). A foodshed was only used in further analysis if it was at least 10% cropland ($\frac{unstable+stable}{total\,cells} \geq 0.1$) and that cropland was at least 80% stable ($\frac{stable}{unstable+stable} \geq 0.8$).

Results & Discussion

Foodsheds

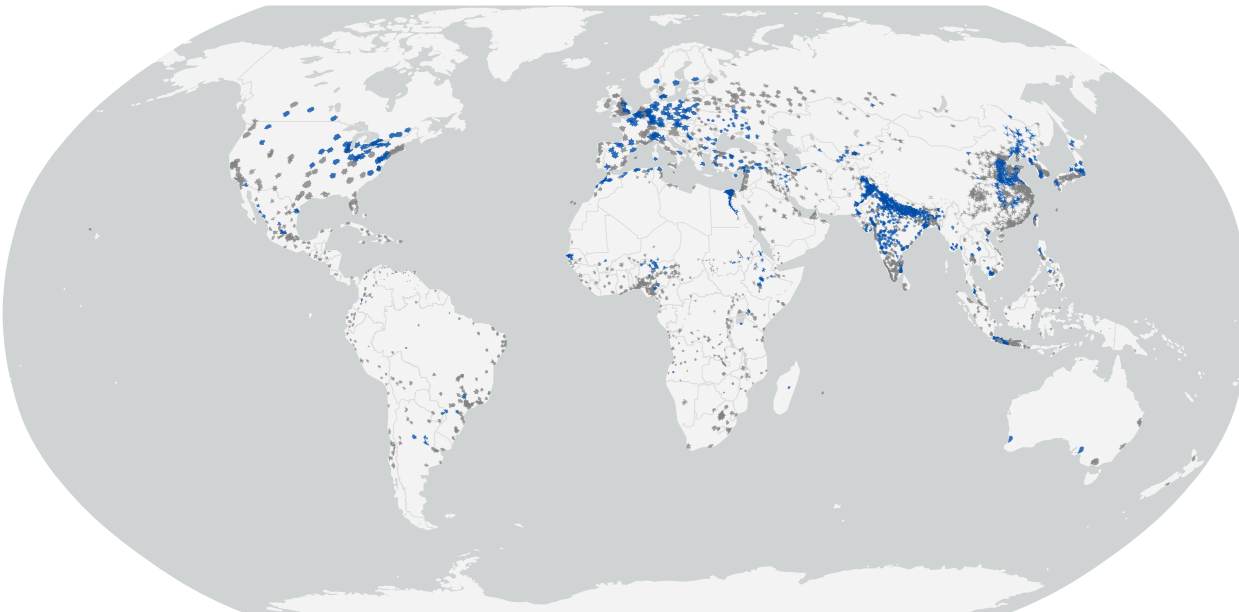
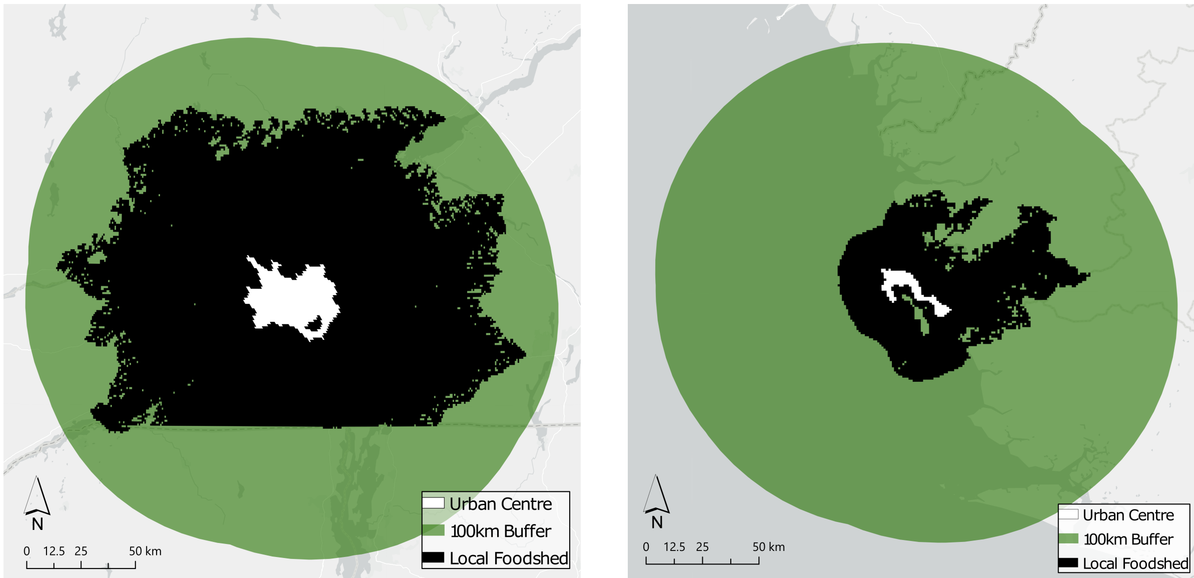


Figure 3: Map of all peri-urban foodsheds, with those that meet the stability requirements displayed in blue and all others displayed in dark gray. All map data source attribution can be found in the Supplementary Information.

Ultimately, the urban centre selection and generation of the travel-time-based catchments yielded 2,425 unique foodsheds. These had a global extent, with a particularly high density of catchments in Europe, China, India, and parts of Sub-Saharan Africa (Figure 3). My analysis did not account for overlap of these catchments to enforce a maximally inclusive foodshed for each urban centre, though this does not reflect the true distribution of resources in these areas, as more accurately modelled by others (Cattaneo, Nelson, and McMenomy 2021). However, these foodsheds did more accurately represent the true "local" catchment of an urban centre, conforming to each area's unique terrain, infrastructure, and borders.

Previous literature addressing local and peri-urban agriculture have primarily used 100 km buffers or the extent of a 30 arc minute cell as a quick way to capture the locality of a given city (Thebo, Drechsel, and Lambin 2014; Kinnunen et al. 2020). Using Weiss et al.'s (2020) Global Motorized Friction Surface's high resolution (30 arc second, ~1 km at the equator), modern, and global extent, these local and regional



(a) Montreal, Canada

(b) Freetown, Sierra Leone

Figure 4: A comparison of the commonly applied 100 km buffer (based on geodesic distance) and the 60-minute peri-urban foodshed used in my analysis for Montreal, Canada and Freetown, Sierra Leone.

catchments represent a more accurate and consistent understanding of the area of influence of a given urban centre. Travel-time-based catchments conform to both the physical and political terrain, adapting to infrastructure conditions, borders, and topography. Its consistency is also an asset: as displayed in Figure 4, while the difference in Montréal's one-hour catchment and 100 km buffer is subtle, it is far more significant for Freetown.

Foodshed analysis has often been approached in two ways: a globally focused analysis that fully models the complicated interactions and interconnections of global food trade networks, and a locally focused analysis that emphasizes the influence of "local food" in a small food system and offers a critique of globalized food systems (Schreiber et al. 2021; Kinnunen et al. 2020; Nelson et al. 2021). This often leaves researchers with a villainous choice between a low-resolution global investigation or a high-resolution local study that carries fewer significant implications for other areas of the world. This thesis offers a new approach to the study of individual foodsheds at a global scale by generating unique travel-time-based catchments (an analogue for a local foodshed) for each individual urban centre. This individuality, while exceedingly useful, revealed a major limitation to this approach: its calculation time. For my thesis, the generation of the urban centres and their associated catchments took around three full weeks of processing time, not including the time required to learn, write, and debug the code.

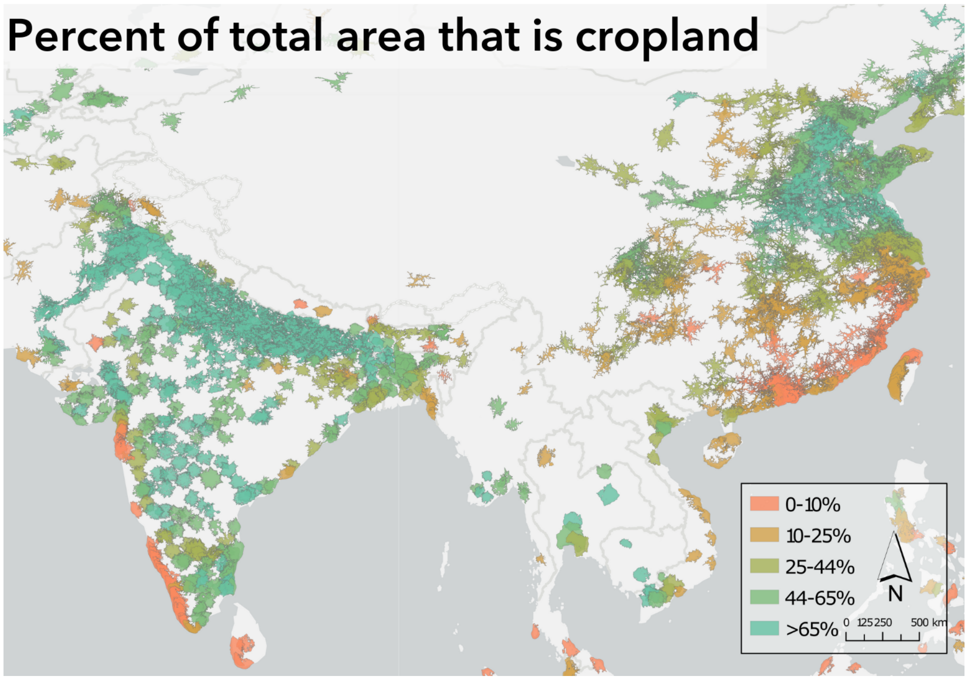
Cropland stability

Calculating the cropland stability revealed stark geographic patterns in its variation. As displayed in Figure 6 and Table 2, 929 peri-urban foodsheds met both the cropland stability threshold of $\geq 80\%$ and the total cropland threshold of $\geq 10\%$. However, their variation mirrors other established cases of large changes in peri-urban land use. Figure 5 demonstrates this, with significant corridors of stable cropland in Northern India and Northern China while the Western coast of India and Southern China both exhibit little total cropland and stable cropland. One of the most interesting scenarios includes areas that met the minimum total cropland requirement but failed to meet the stability criteria, indicating that there is a notable amount of agricultural activity within the peri-urban foodshed that has changed dramatically over 16 years.

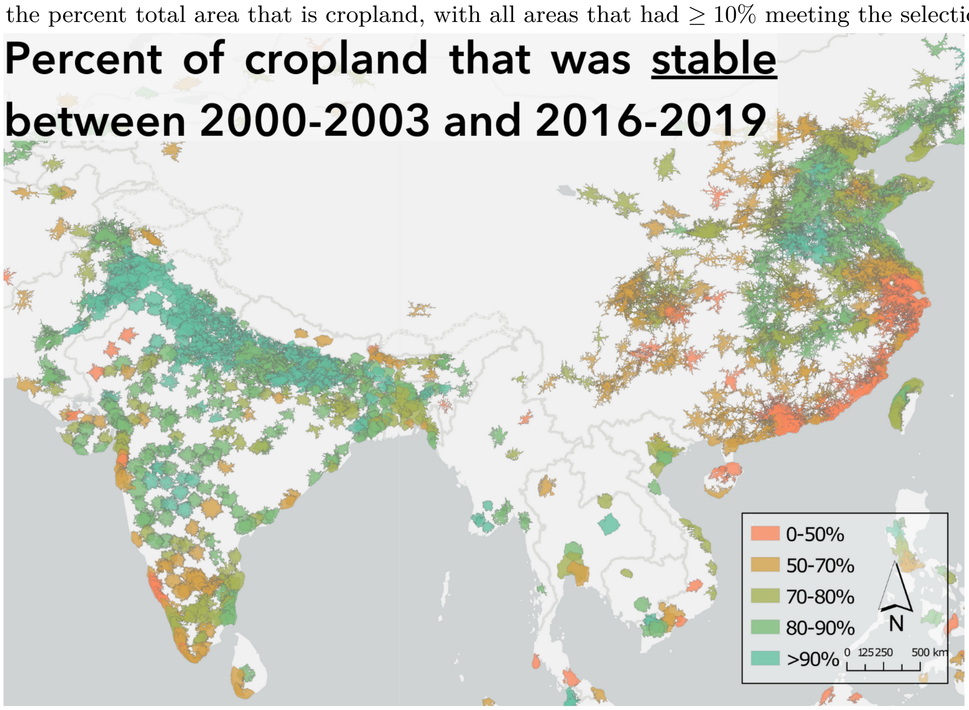
label	variable	Meets stable cropland threshold (>= 80%)	
		FALSE	**TRUE**
Meets total cropland threshold (>= 10%)	FALSE	491 (20.25%)	25 (1.03%)
	TRUE	980 (40.41%)	929 (38.31%)

Table 2: A cross-tabulation of each peri-urban foodshed's total cropland and stable cropland requirements with each combination's percentage of all 2,425 foodsheds shown.

Evaluating the stability of these croplands accomplishes two tasks: it identifies patterns of rapid peri-urban land use change and offers a powerful tool to validate fixed-time datasets for use with temporally expansive methods. While this approach to evaluating peri-urban cropland stability spans only 16 years of the ideal 30 for an investigation applying climate data, it uses the current best available datasets to do so. The simplicity of this approach allows it to be easily applied for future studies and used within a foodshed to identify areas experiencing major shifts in land use patterns.

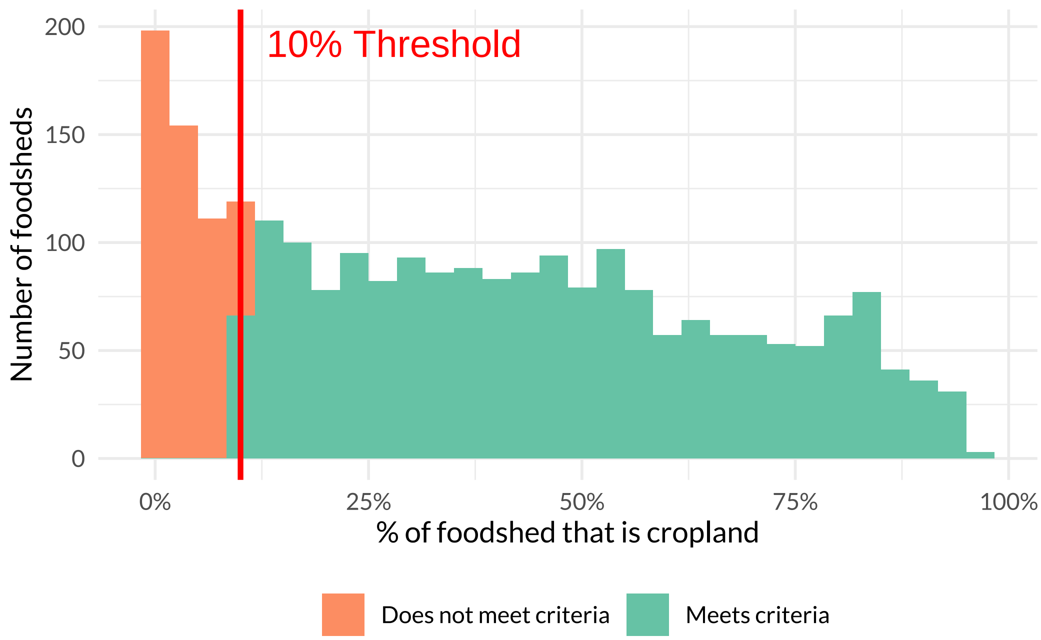


(a) Map of the percent total area that is cropland, with all areas that had ≥ 10% meeting the selection criteria.

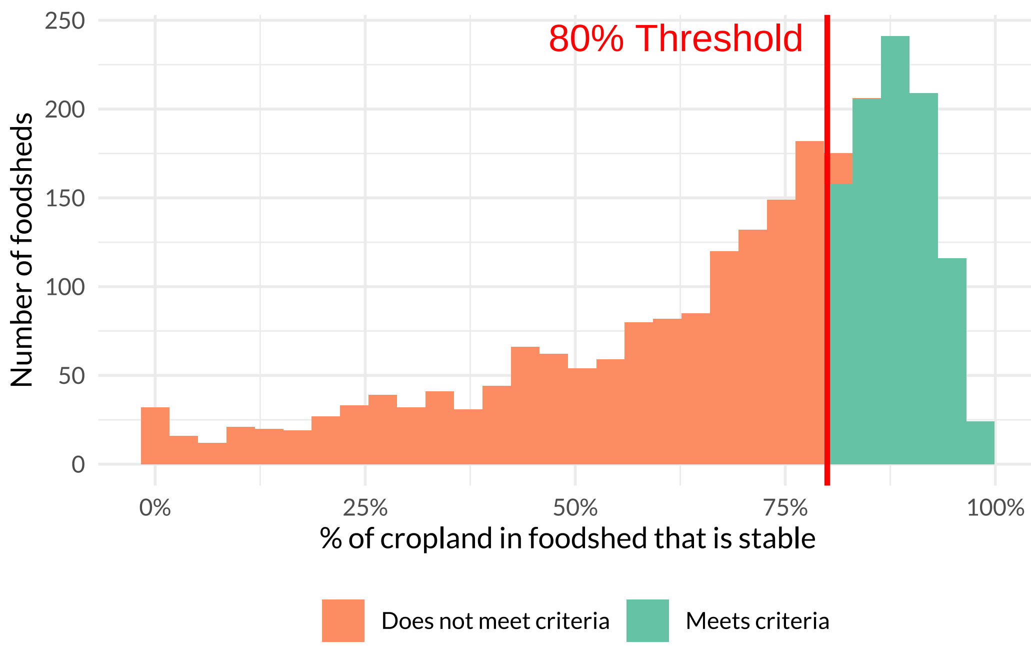


(b) Map of the percent cropland that was stable in 2000–2003 and 2016–2019, with areas that had ≥ 80% meeting the selection criteria.

Figure 5: Maps of total cropland extent within foodshed (a) and the stability of cropland (b) in South and Southeast Asia between 2000–2003 and 2016–2019.



(a) The distribution of each foodshed's percent total cropland with the cutoff of $\geq 10\%$.



(b) The distribution of each foodshed's percent stable cropland with the cutoff of $\geq 80\%$.

Figure 6: Histograms of the cropland stability metrics of total cropland and stable cropland.

A heuristic to determining crop-specific exposure to extreme temperatures

Zooming in on city-specific 'extreme' temperatures

I now turn to my proposed method for applying the peri-urban foodshed catchments to assessing climate change applications, specifically, exposure to extreme temperatures. As previously discussed, extreme heat is deadly to crops, but how do we quantify the "extreme"? There are two methods applied in the literature: a threshold temperature above which the crop's yield begins to fail, or the 95th percentile of maximum temperatures that the crop is exposed to (Jackson et al. 2021; Zhu and Troy 2018; Mueller et al. 2016). The threshold approach involves identifying a crop-specific threshold and identifying growing days with a daily maximum temperature that exceeds that value (Jackson et al. 2021). However, using the same daily maximum temperature data, we can consider the 95th percentile of this data for a given area or cell. This can be helpful to assess the differences in the intensity of exposure to extreme temperatures in different areas, rather than the duration of the exposure. It should be noted that under a normal distribution of temperatures, a higher 95th percentile exposure would also indicate a greater duration of exposures to lower percentiles (e.g., if the 95th percentile value is 41°C and its threshold of 35°C is at the 80th percentile, 20% of all daily maximum temperatures the crop is exposed to will be above its threshold temperature). However, while not requiring a specific threshold temperature, the 95th percentile approach is innately comparative. Previous papers applying this comparative method did so at the regional, national, and continental scales (Mueller et al. 2016; Tuholske et al. 2021).

Proposed framework and workflow

With any city-specific foodshed available for comparison at any selection of scales (and involving any number of possible crops), I selected the 95th percentile application (Figure 7) to avoid the need to determine a crop-specific threshold temperature. This proposed method takes advantage of the three best available products to use with the 1 km foodsheds: irrigation-specific agricultural data from MIRCA2000, recently published global and irrigation-specific crop calendars from GGCMIP, and the 1 km daily temperature data from CHELSA-W5E5 (Portmann, Siebert, and Döll 2010; Jägermeyr, Müller, Minoli, et al. 2021; Karger et al. 2023). While a crop-agnostic approach could be applied (as discussed previously), it is difficult to identify a crop-agnostic growing season. Using GGCMIP's crop calendars, a number of major crops can be investigated, including spring and winter wheat, maize, rice, and soybeans, as well as more locally relevant crops such as pulses and cassava (Jägermeyr, Müller, Minoli, et al. 2021). In addition to its global extent, it also provides

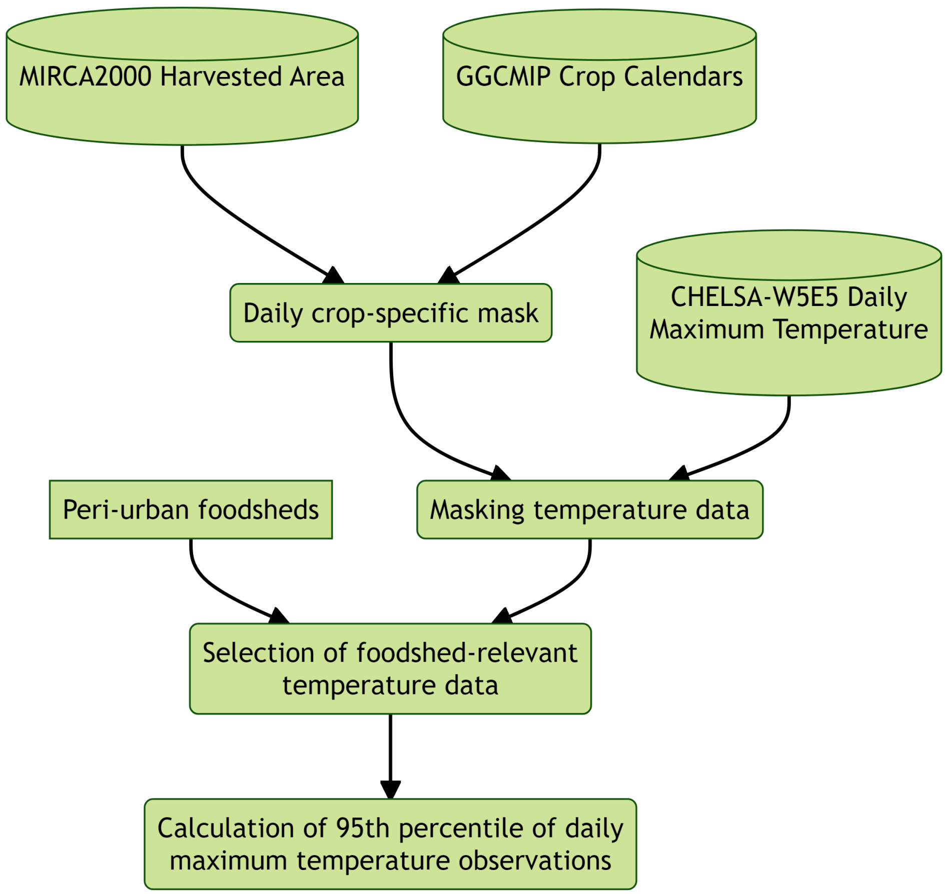


Figure 7: My proposed workflow for determining the crop-specific exposure to extreme heat.

different calendars based on irrigation method, making it ideal for use with MIRCA2000. CHELSA-W5E5, while novel, is being used as a key piece of the high-resolution ISIMIP 3a experiments (Karger et al. 2023). Through a combination of these methods, it is possible to take full advantage of the high resolution of the 1 km peri-urban foodsheds by downscaling both the GGCMI crop calendars and MIRCA2000 to include any 1 km cell that contains a selected crop for an inclusive approach.

In all, this offers a novel approach to determining the specific exposure of peri-urban foodsheds to extreme temperatures and can be adapted to a threshold temperature if preferred. However, I believe this would reduce the power of its conclusions due to the difficulty of establishing a strict threshold for a crop. While this heuristic takes full advantage of the high resolution of the travel-time foodsheds and temperature data, it requires significant computational effort to complete. In its optimized form, every calculation for 1986–2016 will be performed 1.2 trillion times (every tile present in the CHELSA-W5E5 for that time period). Approaching this by breaking the calculations into sectors would be ideal, though cropping such a large dataset does require a lengthy amount of time. Ultimately, it offers foodshed-specific information on individual crops' exposure to extreme heat, and can be readily extended to extreme cold by using the daily minimum temperatures also provided in CHELSA-W5E5.

Concluding Remarks

In this thesis, I have sought to quantify how croplands have changed in peri-urban regions globally. This is of critical concern, particularly since some of the best, most intensively managed, and most productive croplands are located near cities (Thebo, Drechsel, and Lambin 2014). Though the distance of the travel-time foodsheds vary, less than half of all foodsheds with some cropland had stable agriculture between 2000–2003 and 2016–2019 (Table 2). While it's difficult to make a direct comparison to Thebo et al.'s (2014) study, my findings from the cropland stability analysis represent a dramatic upheaval of the potential local urban food supplies for many cities. Being urban centre-specific means that this information can be used to identify cities with high cropland stability and those with low cropland stability to compare their policy decisions and other circumstances leading to this result.

Additionally, ensuring that a city's agriculture is stable is crucial for a temporally expansive analysis. This is especially useful for a temperature focused analysis as it reduces the complexity of attempting to model shifts in peri-urban agriculture for the span of the study. However, with only 38% of peri-urban croplands meeting the stability and cropland requirements (Table 2), this may be less effective as a validation method than I had expected. Nonetheless, determining the extreme temperature exposure is critical to identify which peri-urban food systems are at greatest risk of disruption. Being able to differentiate these peri-urban regions could aid in building more resilient food systems and optimizing the use of climate adaptation technologies to avoid these future disturbances. My proposed framework for calculating these extreme temperature exposures can be the tool to do this, offering city- and crop-specific exposure at a higher resolution to deliver the most relevant extreme temperature information for the world's population centres.

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Supplementary Information

Map data source attribution.

Figure 3 projected in Robinson (EPSG:54030). Basemap provided by Esri using data from Esri, TomTom, FAO, NOAA, and the USGS. Peri-urban foodsheds and cropland stability data created by the author.

Figure 4a projected in NAD83 (CSRS) / MTM zone 8 (EPSG:2950). Basemap provided by Esri using data from la Ville de Montréal, Esri Canada, Esri, TomTom, Garmin, FAO, NOAA, USGS, EPA, NPS, NRCan, and Parks Canada.

Figure 4b projected in Sierra Leone 1968 / UTM zone 28N (EPSG:2161). Basemap provided by Esri using data from Esri, OpenStreetMap contributors, TomTom, Garmin, FAO, NOAA, and the USGS.

Figure 5 projected in WGS 1984 (EPSG:4326). Basemap provided by Esri using data from Esri, TomTom, Garmin, FAO, NOAA, and the USGS. Peri-urban foodsheds and cropland stability data created by the author.