

## **Spatial linkages between the growth of urban centers and major global cropping areas: historical relationships and contemporary conditions**

### **1. Abstract**

The historical relationships between urban population growth and agricultural lands is not well understood and has not been examined at global scales. Although it is widely quoted that cities have developed near agriculturally productive lands, there is little empirical evidence that supports this idea. Here, we estimate spatial proximity between urban population centers and major global cropping regions for the last 5,000+ years. To examine this relationship, we digitized, geocoded, and combined multiple datasets of city-level population data from 3700 BC to 2000 AD. This global, city-level population dataset was then compared with global croplands raster grids for the concurrent time period. We then determined geographic mean centers for both population and cropland data to determine variations in this spatial relationship. Results show that although global cropland mean centers follow a clear trend, global population centers do not due to bias in the population dataset. As a result, determining a clear relationship between the two variables is challenging. Next steps include 1) interpolating the population dataset to determine its effect on the resulting mean centers 2) a regional scale analysis on India and Europe given high temporal and spatial resolution of population values.

### **2. Introduction & Rationale**

The UN projects that by 2030 nearly 5 billion people will live in urban centers (UN 2012), and in that time urban land cover is projected to increase by 1,527,000 km<sup>2</sup> (Seto et al. 2011). In order to feed this growing world population, it is predicted that agricultural production must increase by 70% before 2050 (Brunisma 2009). However, land that is best suited for agricultural development is often similarly appropriate for urban growth, resulting in a spatial proximity or overlap between these two land-uses (Stamp 1941, Imhoff et al. 1987).

Recent urban growth forecasting (Seto et al. 2011) has led to an increase in associated agricultural land loss analyses from economic, remote sensing, soil science, and land-use planning perspectives. (Avellan et al. 2012, Christensen et al. 2014, Pandey et al. 2014, Reistma et al. 2014). Many of these analyses have adopted the well-accepted, yet not empirically proven foundation that cities have developed near agriculturally productive lands over time (Nizeyaimana et al. 2001, Doos 2002, Imhoff et al. 2004, Seto et al. 2010, Avellan et al. 2012a, Christensen et al. 2014). It is theoretically understood that during historic time periods, given higher food transport costs and limitations, cities developed in agriculturally productive areas (Bairoch 1988, Steel 2009, Christensen et al. 2014). In other words, the higher agricultural potential of an area, the higher the potential population density achievable. However, there is little empirical evidence that supports this idea and it has not been examined at global scales.

To better understand agriculture's role in urban growth and our current urbanization and food security concerns, it is important to critically evaluate and measure past relationships. These relationships will serve to quantify links between urban centers and agricultural lands, determining if access to major agricultural lands is positively correlated with urban growth.

Specifically, we are interested in determining if/when a distinct shift in the spatial relationship between the location and size of human settlements and major global cropping regions occurs.

Quantifying this historical relationship at a global scale is significant because a decoupling of our urban population from our global croplands could lead to a more vulnerable global food system, leaving cities more susceptible to natural disasters and shocks to the food system (Ramankutty et al. 2002, Reitsma et al. 2014). Understanding the history of this relationship may also lead to important insights into why some cities have developed while others have not. It may also help to explain aspects of the spatial distribution of cities today. In order to understand the effect of urbanization on food production, we must better understand the historical relationship between urbanization and agriculture.

This study makes the first attempt to quantify the historical relationship between urban centers and global croplands for the last 5,000 years. This relationship is measured using a methodological approach sensitive to the challenges and inherent uncertainty of quantifying relationships at long historical timescales and differing spatial resolutions. Here, we use Geographic Information Systems (GIS) techniques to determine global mean centers for both population and cropland areas across the 5,000 year time period. Distances between these two centers are then measured and compared for each established time period. Once this relationship is established, future food production implications are discussed.

### 3. Background

Although it is widely quoted that cities have grown in the most productive lands (Nizeyaimana et al. 2001, Doos 2002, Imhoff et al. 2004, Seto et al. 2010, Avellan et al. 2012a, Christensen et al. 2014), there is no empirical evidence that supports this idea. Here, we contextualize and synthesize the current literature focusing on the historical relationship between agriculture and urbanization, the current interplay between these two processes, and the significance of this historical relationship for future global food security. Although archaeologists and historians have examined this relationship on a smaller, site-specific scale, it is important to note that no previous study has empirically examined this historical relationship on a global scale, taking into consideration a wide range of cities and global cropland coverage. Therefore, a substantial deficiency in the current literature exists. This study intends to fill this research gap by determining spatial correlations between 5,000 years of urban population growth and major global cropping regions.

Historically, it is understood that civilizations need certain resources, such as reliable access to water and food within a favorable climate zone, to survive and flourish (Ramankutty 2002, Sinclair 2010, Avellan 2012b). It can then be logically inferred that cities would have developed in close proximity to both water and potential agricultural land (Ramankutty et al. 2002, Doos et al. 2002, Seto et al. 2010), spatially linking our urban areas and croplands worldwide. Agricultural production, starting in about 10,000 BC, is often considered one of the largest universal enablers of sustained and large-scale human population growth (Pryor 1986, Bairoch 1988, Kates et al. 1990). Conversely, as a population grows in size, food gathering and production methods must

intensify (Cohen 1977, Pryor 1986) and this intensification can then support a larger concentrated population. It is clear that a link between the size of a population and its food supply exists.

In order to better understand the history of the relationship between agriculture and urbanization, it is necessary to understand the development of each process individually. Here, we will first discuss the historical development of agriculture followed by the historical development of cities. After each area is explored individually, we will discuss the historical relationship between these two processes.

### *History of Agriculture*

Here, we define agriculture as “the artificial means of increasing the growth and yield of a given plant, or plants, over, or at the expense of, other plants, and the culturally derived knowledge and techniques employed in such activity varies from the extremely simple to the highly complex” (Ferdon 1959). Yet even after providing a common baseline for agriculture itself, causes for the invention of agriculture remain non-unified. Common potential origins include: the result of chance, changes in climate, a need arising from demographic pressure/population growth, or to achieve a balance in a region’s food portfolio (Ferdon 1959, Cohen 1977, Pryor 1986, Bairoch 1988, Tannahill 1988).

Considering these possible origins, two in particular - population growth and climate change - are generally most readily accepted as plausible for a settlement’s transition from hunting and gathering to agriculture-based. Considering population density, the logic is as follows: as the population of a region increases, food gathering activities must intensify to provide for a settlement’s inhabitants (Cohen 1977, Pryor 1986). At a given point, it becomes evident that agriculture provides higher returns on labor for the settlement as a whole as opposed to hunting and gathering (Pryor 1986). However, although this progression of development is logical, climate change may also have played a significant role in this agricultural transition.

At the start of the last glacial retreat of the Laurentide ice sheet about 12,000 ago, climatic conditions supported fast-growing plants, particularly fast growing grasses (Tannahill 1988). These grasses could complete a growing cycle in the Mediterranean region before the onset of intense summer temperatures, which desiccated the slower growing competitors. As a result, wheat and barley developed on these suitable lands (Tannahill 1988).

These two processes – glacial retreat and population increase - are not unrelated. Areas of glacial retreat which supported fast growing vegetation, also supported the emergence of game. These two food sources could now also support a larger population (Bairoch 1988). Indeed, it appears as though both improving climatic conditions and an increase in population are linked.

Despite the uncertainty of the origin of agriculture, its adoption has been undeniably universal (Cohen 1977, Bairoch 1988). Just after the last glaciation, nearly all humans survived by hunting and gathering, while at the turn of the century nearly every civilization subsisted through farming (Cohen 1977, Bairoch 1988).

The earliest known site of agricultural development is the Middle East (Bairoch 1988). It was here where wheat agriculture originated (Childe 1934). During this time in history, humans began to domesticate plants and animals (Vavilov 1926). Next, agriculture spread through the Mediterranean, eastern China, and northern India due to the existence of irrigation around the year 0 AD (Goldewijk et al. 2010). From 500 AD – 1600 AD, civilizations and agriculture flourished in Central and South America (Goldewijk et al. 2010). By 1600 AD, a distinct global increase in population had occurred (Goldewijk et al. 2010). Today, major cropland areas exist in Europe, North and South America, Asia, and Australia, with cropland area increasing in Africa.

As the development of croplands spread across the globe, settlements also developed concurrently. In fact, some argue that agricultural abundance permitted the “birth of ancient civilizations, the development of modern industrial societies, technological innovations, [and] frequent changes of lifestyles” (Yasuda 2002), since this agricultural abundance allowed time for a settlement’s development of specialized activities. Regardless of which origin, agriculture or civilization occurred first, both are essential in understanding cities and their food supplies both today and through history.

### *History of Cities/Settlements*

Once again, we begin by providing a baseline definition of a city. However, it should be noted that different definitions exist as to what constitutes a city or urban area. Here, we will start with a definition provided by Cowgill: “a city [is] a permanent settlement within the larger territory occupied by a society considered home by a significant number of residents whose activities, roles, practices, experiences, identities, and attitudes differ significantly from those of other members of the society who identify most closely with ‘rural’ lands outside such settlements” (Cowgill 2004).

In order to create this urban environment, Bairoch argues that one or more of 5 conditions must be met:

1. The existence of full-time craftsmen, furnishing evidence of a division of labor
2. The existence of fortifications or walled enclosures thus distinguishing the city or town from the village, which remains open
3. A population of a sufficient size and above all density
4. A specifically urban habitat; houses built of durable materials, habitations arranged so as to form streets and so forth
5. Permanent settlements, as opposed to transient encampments

(Bairoch 1988)

Considering these conditions, the role of agriculture in city development can be related to both 1 and 5. An agricultural-based society which concentrates the growing of food to specific people, places, and times allows for a division of labor amongst other settlement inhabitants. Agricultural-based societies also create permanent settlements (number 5 above) due to the investments of time and resources to the development of croplands. However, it is clear that other criteria exist for creating and constituting an urban environment.

Historically, it is believed that urban areas mainly developed in areas most suitable for survival and rich with natural resources. These areas often included fertile soil regions on river deltas, oasis, or at the edges of lakes with favorable climates (Avellan 2012b). However, suitable agricultural land is often paired with favorable climate/weather conditions. These favorable climate conditions could be a more significant factor in urban development than agriculture itself (Christiansen et al. 2014). The first Neolithic settlements, such as Jericho and Catalhoyuk, were located in the fertile plains of river deltas approximately 12,000 years ago (Sinclair 2010). During this Neolithic period, society became more developed organizationally and often had more extensive communication and irrigation networks (Sinclair 2010). It here in the Neolithic period where the transition from hunter-gatherer lifestyle to agricultural settlements occurred. By 4000 BC, the first cities, such as Uruk, Eridu, and Sumner began to emerge (Bairoch 1988, Modelski 2000, Sinclair 2010).

Today, approximately 40% of the Earth's surface is covered by croplands and pastures (Ramankutty et al. 2008), while urban areas cover approximately 0.5% of Earth's surface, ranging from 0.17% of land area in Africa to 1.78% land area in Europe (Schneider et al 2010). These urban areas are also expanding at unprecedented rates – twice as fast as the population itself (Seto et al. 2011). Recent research has shown that by 2030, 4.5% of global croplands will be lost to urban expansion (Reitsma et al. 2014). More significantly, a significant portion of this land is considered to be highly productive (Nizeyaimana et al. 2001, Imhoff et al. 2004, Reitsma et al. 2014). Considering the majority of the world's most productive land is already under cultivation (Ramankutty et al. 2002), we are losing prime agricultural land without a readily available replacement. Here, we examine how this spatial relationship between urban areas and global croplands has changed over the last 5,000+ years.

## 4. Data & Methods

### 4.1 Urban Population Growth Dataset

#### *Background*

As Lewis Mumford notes in the forward to the first edition of Tertius Chandler's book, *Four Thousand Years of Urban Growth*, "one of the most serious defects of historical urban studies is the lack of specific statistical information about the area, the density, and the population of cities" (Chandler 1987). In an attempt to fill this research gap, Tertius Chandler devoted 30 years of his academic career to measuring and interpolating global, city-level population estimates through time.

Chandler's persistent and detail-oriented demeanor led to the development of one of the most complete, city-level population datasets today. Chandler's approach involved 1) collecting existing population and demographic information for the major cities of the world through history and 2) developing methods to estimate city-level population values where these population figures did not exist.

Chandler utilized a wide range of sources to complete this task: censuses, scholarly reports,

traveler's diaries, encyclopedias, gazetteers, travel guides, librarians, scholars, tax documents, streets, public baths, disasters (lives lost), and religious histories of cities (Chander 1987). From these sources, Chandler pieced together global city-level population estimates through time by first obtaining a demographic factor for a particular city, such as number of loaves of bread sold, and a relevant multiplier. Considering Italy as an example, a relevant multiplier was determined through referring to a city/cities where both the number of loaves of bread sold and the corresponding population value were known for a given year. The population value could then be divided by the number of loaves of bread sold to determine the relevant multiplier for a particular country during a particular time period. This multiplier could then be used for similar cities within the same country.

However, this dataset is not without challenges and limitations. Despite Chandler's accomplishment, the resulting population dataset is temporally and spatially sparse. Temporally, gaps in measured or interpolated population values can be hundreds or thousands of years in duration. Spatially, only 1,749 cities are included in the complete dataset for the entire time period. Therefore, it is clear that this dataset alone is not an accurate global representation of population values through time. Rather, it highlights the population values of important global cities during important time periods. This fact limits the scope of analysis possible with this dataset.

As a result, George Modelski's dataset published in *World Cities: -3000 – 2000*, was combined with Chandler's work to extend the dataset. The combination of these two datasets was logical and feasible due to the fact that Modelski himself considered his work an extension of Chandler's original dataset – "filling in gaps and enriching it with new information" (Modelski 2000). Modelski's additional work adds 190 cities and 1475 years to the final population dataset used for this analysis.

Finally, it is also worth recognizing Chandler believed the city and countryside were "distinct human and economic institutions," which were not co-dependent and developed separately. He did not believe that urban development depended on rural productivity (Chander 1987). Here, we attempt to determine if there is in fact a measurable relationship between cities and their surrounding hinterlands. More specifically, is a city's size correlated to its proximity to agricultural land?

### ***The Datasets***

Chandler and Modelski's population datasets were digitized, geocoded, and combined to create one 6,000 year record of global, city-level population data (Chandler 1987, Modelski 2003). Chandler's population dataset, which encompasses the years from 2250 BC to 1975 AD, was received in book text format. This text was manually transcribed into an excel spreadsheet, noting city population values for each available year. The final dataset was checked twice by two research assistants for transcription errors and accuracy. Modelski's dataset builds upon Chandler's work and was used to extend this population record both forward and backward in time, from 3700 BC to 2000 AD. Modelski's dataset was received from the author in digital table format. These table were then converted to excel tables with similar format to the Chandler

dataset.

After transcription of both datasets was complete, each city was geocoded, or assigned a corresponding longitude and latitude value. Originally, mass geocoding software programs, such as CartoDB, were used. However, due to the long timescale of the population record and changes and similarities in city names through time, these results proved to be highly inaccurate. Next, the Geonames database ([www.geonames.org](http://www.geonames.org)), which contains a comprehensive list of cities with populations over 10,000 inhabitants and its corresponding longitude and latitude, was used in a table join based on city name of both tables to match cities with their longitude and latitude values. Although more successful than the initial approach, numerous error remained. These errors were remedied by a one-by-one look-up in Google Earth and Wikipedia's GeoHack toolservers, which provides map sources and geolocations based on the work of Egil Kvaleberg (<https://wiki.toolserver.org/view/GeoHack>). The Ancient Locations database and Getty Thesaurus of Geographic names was also used for ancient city locations. Unmatchable cities due to changes in names and spellings were discarded. The final geocoding result had an 85% match rate. Cities were also ranked based on the accuracy of their geocoded match. These two datasets were then combined using R statistical software to create one large population dataset spanning the years 3700 BC to 2000 AD.

## 4.2 Major Global Cropping Regions Dataset

### *Background*

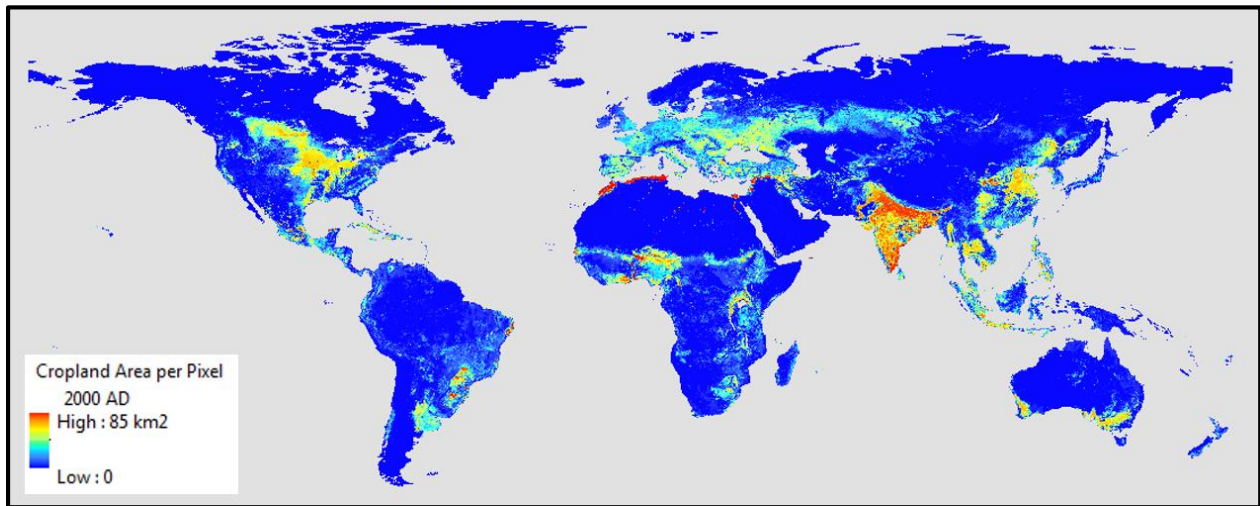
Multiple datasets exist which attempt to reconstruct historical global croplands at various timescales and spatial resolutions (Ramankutty 1999, Pongratz et al. 2008, Goldewijk et al. 2010). This analysis utilizes the HYDE 3.1 database of historical land use, which is at a 5' longitude/latitude grid resolution due to its availability for long timescales. The dataset records global cropland pixel values from 10,000 BC to 2,000 AD. Although other datasets, such as Ramankutty and Foley's Global Cropland and Pasture Dataset (1700 AD – 2007 AD) or the Food and Agriculture Organization's (FAO) Global Agro-Ecological Zones (GAEZ) dataset, may provide more accurate cropland and production data for more recent time periods, both of these datasets lack a long historic perspective, which is essential to this analysis.

### *Dataset*

The HYDE 3.1 database determines historical pixel-level cropland values using specific allocation algorithms which change over time and combines this cropland data with satellite information to create time sensitive, spatially explicit maps (Goldewijk et al. 2010). Global croplands are estimated at an 85 km<sup>2</sup> pixel level at the equator. Factors used to predict cropland values per pixel include: soil suitability, proximity to coastal areas and river plains, and favorable topographical slopes. This database excludes areas of low population density (less than 0.1 person per km<sup>2</sup>) due to lack of need for agriculture, while established urban areas were also excluded due to lack of space for agriculture (Goldewijk et al. 2010). Finally, areas with an annual mean temperature less than 0°C were also excluded due to unfavorable growing temperatures.

In order to create historical cropland maps, the database uses a weighted combination of a

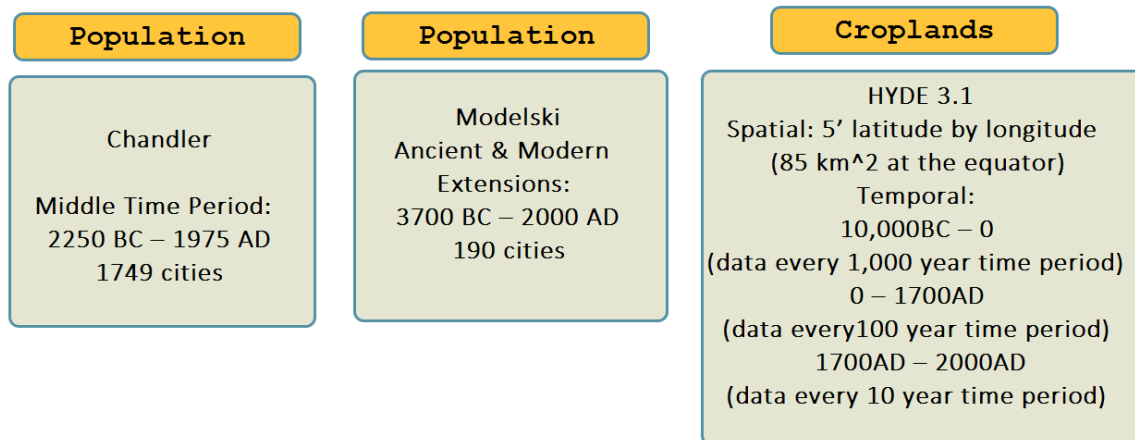
current satellite cropland map for the year 2000 AD and a historical map which uses the 6 factors described above to determine historical croplands. Each of these maps are used as weights to an overall function to determine global croplands through time. During the most ancient time period, the historical map carries most of the weight, influencing the designation of cropland pixels. As time progresses, the historical map weight decreases while the current satellite weight increases until the current satellite map determines the location and value of cropland pixels in the year 2000 AD (Goldewijk et al. 2010). (figure 1)



**Figure 1:** Example of Global croplands for 2000 AD from the HYDE 3.1 Database

It is important to note that the HYDE 3.1 database identifies global cropland locations, meaning where croplands actually are estimated to exist through time. It does not measure soil productivity. Therefore, this dataset is capable of determining if there is a correlation between city population size and proximity to agricultural croplands. It is not capable of providing information about whether or not cities developed near the most agriculturally productive lands through time. This limitation exists because we cannot determine if cropland exists on the most productive lands in the database. Other limitations of the HYDE database include large uncertainty in predictions as we move back in time. Uncertainties are estimated at: 5% in AD2000, 10% in AD1900, 25% in AD1800, 50% in AD1 and 75% in 10,000BC (Goldewijk et al. 2010).





**Figure 2:** Data summary

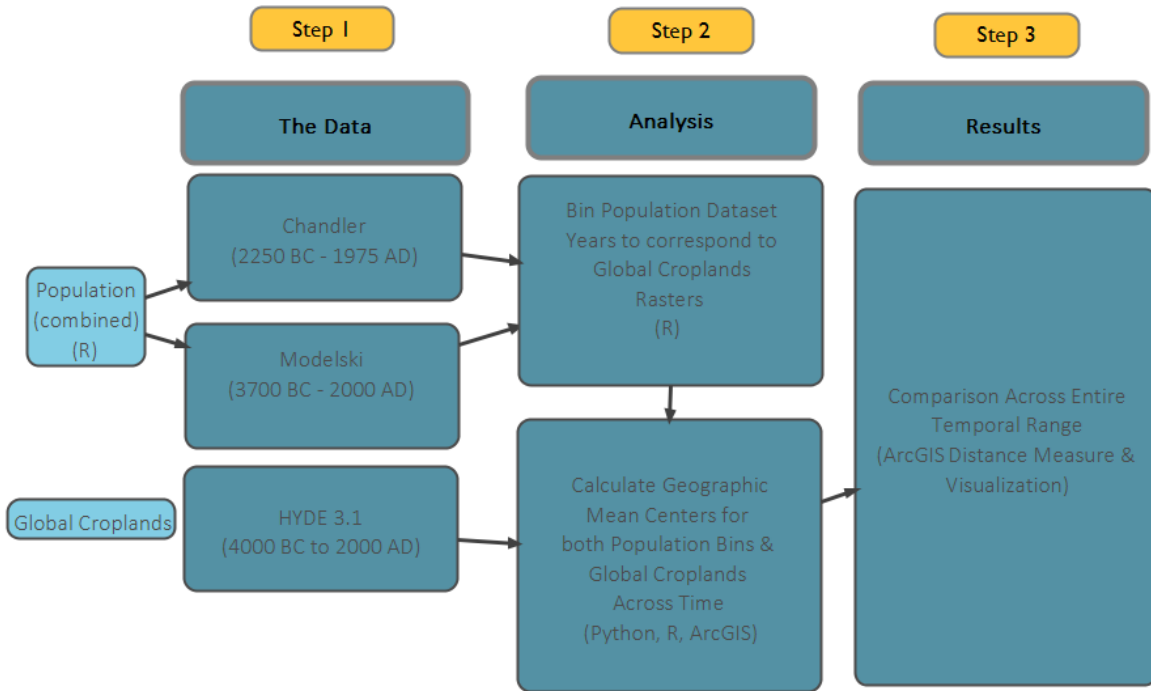
Once the population and croplands datasets were identified and prepared, the two population datasets were combined into one large dataset using R statistical software. Here, new cities and new years of population data were added to the existing format of the Chandler dataset.

Next, the data set was binned. Binning involves grouping the population data into defined time periods. This technique was necessary due to the spatial and temporal sparseness of the population dataset. By combining multiple years and city populations into one time-bin, the number of observations per time period was increased. When more than one population value for an individual city within a time bin was observed, the mean population value was used.

Population bins were created with a temporal resolution corresponding to the temporal resolution of the HYDE 3.1 cropland raster grids. Therefore, given the years of the analysis, 3700 BC through 2000 AD, 52 HYDE raster grids were necessary to represent croplands through this time span. As a result, 52 total population time bins were created, matching this established time scale. Observations were binned at the following temporal scale: 10,000BC – 0 (data every 1,000 year time period: 4 grids/bins), 0 – 1700AD (data every 100 year time period: 17 grids/bins), 1700AD – 2000AD (data every 10 year time period: 31 grids/bins).

Next, global mean centers for each of the 52 population bins and cropland rasters were calculated, respectively using both R statistical software and GIS. Both datasets were projected from a geographic coordinate system (WGS 1984). WGS 1984 is a geographic projection which equates east/west longitude positions on the globe to right/left horizontal positions on the globe, while north/south latitude positions on the map are related to top/bottom vertical positions on the map (Tomlin Handouts 2014). Therefore, when trying to represent this spherical world surface on a flat piece of paper, distances further from the equator are greatly distorted. Here, we selected Goode Homolosine, an equal area projection, to more accurately preserve pixel size and later measure distances between mean centers of population and cropland values using the distance measuring tool in ArcGIS.

Finally, point distances between these mean centers were calculated and visualized in ArcGIS. Figure 3 highlights the major steps of the analysis, including tools/software used for each component.



**Figure 3:** Flow chart showing major steps of the analysis

*Step 1* involves creating and combining the population and cropland data. *Step two* involves binning the population data to match the cropland raster grid temporal resolution. Next, geographic mean centers are calculated in ArcGIS and R. *Finally*, distances between global mean centers are measured using the distance measuring tool in ArcGIS. These distances are then compared through time to determine the relationship between city population size and proximity to global croplands.

## 5. Results

### *Croplands*

Results show that cropland centers have shifted from just west of Mesopotamia in 3700 BC eastward toward Asia in the 1700/1800's, back toward Europe in the early 1900's to currently center over north Africa. After early agricultural cropland development near the Fertile Crescent, croplands expand first in Europe and China, followed by India. Next, we see a small amount of cropland expansion in Africa, followed by more substantial development in North America, Europe, South America, followed by Australia (figure 4).



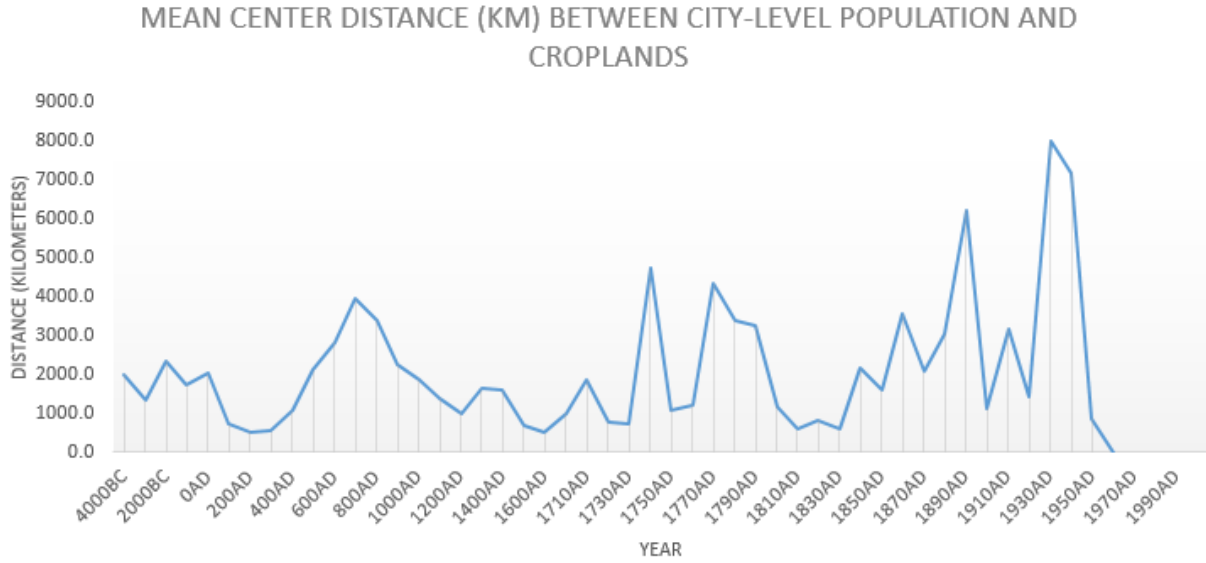


Figure 6: Mean Center Distance – Croplands and Population

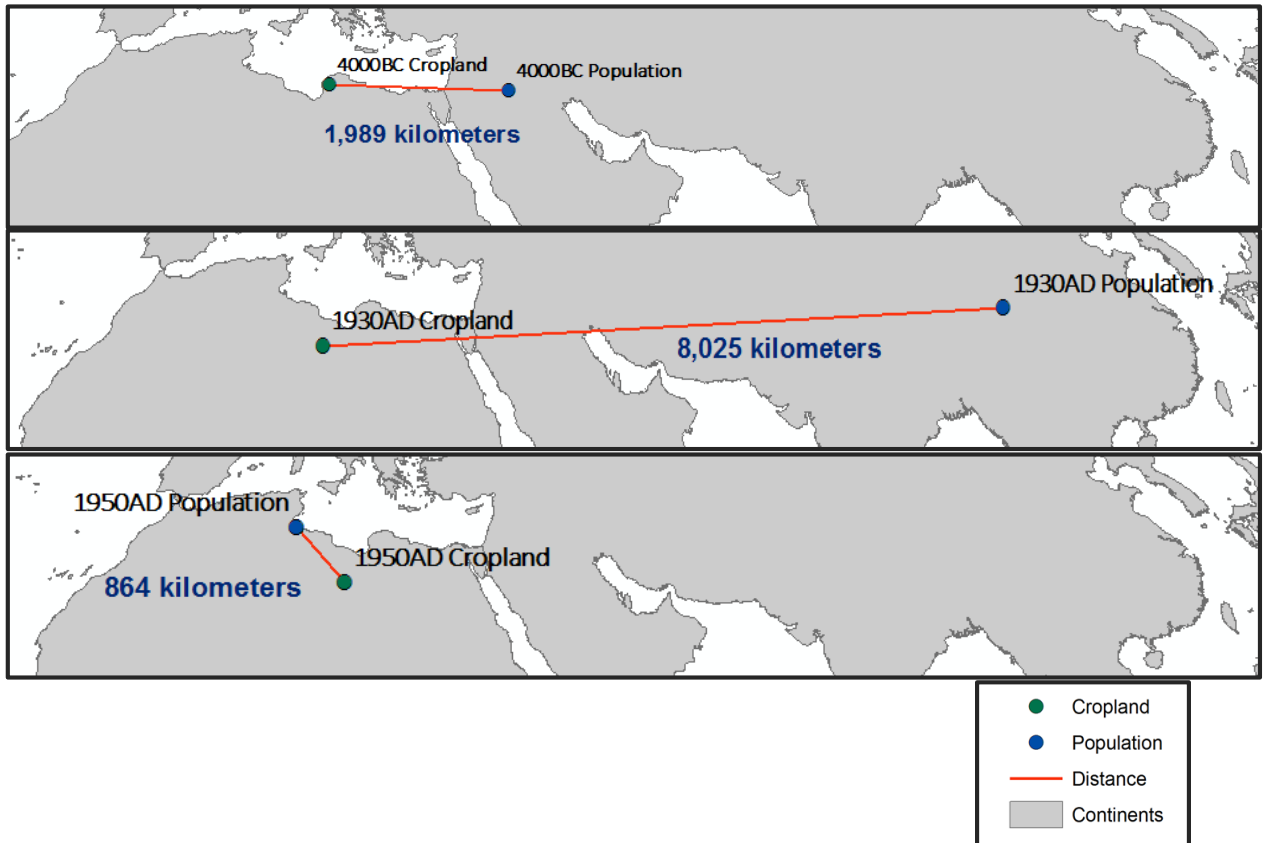


Figure 7: Unclear trends in mean center distances

## 6. Discussion & Conclusion

Calculations determining the distances between global mean centers of population and croplands (draft of table included after references section below) are not showing a clear trend due to biased population data. Possible future directions include:

- 1) Interpolating the population dataset to determine its effect on the resulting mean centers. However, the entire dataset still only contains approximately 2000 cities, which even when interpolated may not cover a sufficient spatial range to be useful/effective for calculating global mean centers.
- 2) Regional Scale Analysis: India and Europe look promising for regional scale analyses given high temporal and spatial resolution of population values.

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Year	Mean Center Distance (km)		
4000BC	1989.8	1750AD	1077.3
3000BC	1333.5	1760AD	1207.1
2000BC	2345.4	1770AD	4330.2
1000BC	1,748.80	1780AD	3399.3
0AD	2013.4	1790AD	3252.8
100AD	715.8	1800AD	1182.0
200AD	506.6	1810AD	581.8
300AD	543.1	1820AD	825.9
400AD	1061.4	1830AD	592.8
500AD	2108.3	1840AD	2149.6
600AD	2826.6	1850AD	1580.7
700AD	3934.7	1860AD	3555.5
800AD	3386.0	1870AD	2065.4
900AD	2264.5	1880AD	3053.1
1000AD	1875.2	1890AD	6240.0
1100AD	1,397.90	1900AD	1128.8
1200AD	1002.3	1910AD	3183.4
1300AD	1632.7	1920AD	1415.7
1400AD	1575.1	1930AD	8025.2
1500AD	677.5	1940AD	7181.0
1600AD	489.2	1950AD	864.0
1700AD	1005.5	1960AD	no population values
1710AD	1846.9	1970AD	
1720AD	780.4	1980AD	
1730AD	724.2	1990AD	
1740AD	4728.6	2000AD	

**Table 1:** Mean Population and Cropland Distance per Time Period