# BACHELOR THESIS

Effect of climate change on the collapse of the Maya civilization

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## Abstract

This study investigates the role of climate change on the societal collapse of the Maya civilization. Archaeologists have been speculating on the rise and fall of past civilizations for several decades and it is becoming more and more evident that there is much complexity involved. This is especially true for the Maya civilization, a once thriving society which crashed seemingly with no direct identified reason. Current available research often has a focus on only one aspect or data source to generate conclusions and few studies interpret their findings with the current climate crisis or discuss whether this is a valid comparison. That is why this research aimed to create an overall image of the effect of climate change on the demise of the Maya civilization. To do so, the following concepts were investigated: Climate change, Societal collapse, the Political system, Precipitation, Population, Crop production, and Forest land. All the concepts were investigated through a meta-analysis. Additionally, Precipitation, Crop production, Population and Forest land were also quantitatively studied with the use of HYDE and FAOSTAT. The data was analysed using ArcMap and Excel. Apart from some exceptions, the literature studies were found to be consistent with the proposed theory that climate change is linked to the societal collapse of the Maya Civilization. There are some uncertainties, especially regarding the extent of the societal collapse as well as the mechanism that caused the climate change. Furthermore, it became clear that the collapse of the Maya cannot be observed in HYDE, thus it is likely that this has not been incorporated into HYDE yet. However, none of the research contradicted the theory, and it seems that the proposed theory is viable. Thus, it is likely that climate change was the overarching factor that set the collapse of the Mayas in motion.

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# Introduction

An important factor for the survival of a civilization is climate, due to its fundamental role in the production of food (Smith & Gregory, 2013). Recently, there has been more discussion of the extent of the role of a changing climate on the fate of a civilization, and more specifically their demise (Lawrence et al., 2016). Historians and archaeologists have been speculating on the rise and fall of past civilizations for several decades and it is becoming more and more evident that there is much complexity involved. This is especially true for the Maya civilization, a once thriving society which crashed seemingly with no direct identified reason (Mott, 2012). One of the most recurrent theories in research is that climate change played a role in the fall of the Maya civilization (Kuil et al., 2016). The proposed theory explains that food production failed due to recurrent droughts, and this resulted in a variety of societal stresses that could have led to the demise of the Maya empire (Haug et al., 2003)

However, there are some compartments of the proposed theory in which research is lacking. Due to the complexity of climate change, most papers only focus on a single data source or aspect to generate conclusions. Most papers are also lacking in quantitative data on how exactly the relation between climate change can cause the fall of a society through a conceptual framework. Furthermore, few studies interpret their findings with the current climate crisis or discuss whether this is a valid comparison.

That is why this research aims to create an overall image of the effect of climate change on the demise of the Maya civilization. This will be done by creating a knowledge database on the Maya empire with the use of a conceptual framework, as well as using the History database of the Global Environment (HYDE) and ArcMap to illustrate the findings with quantitative data. Furthermore, a justification will be given in the discussion to see if using past civilizations as an example for the future is a reasonable interpretation for the current climate crisis.

Achieving this research aim helps science by providing a clearer image on the downfall of the Maya civilization and further proves the theory of the importance of a stable climate for a society to thrive. It could prove useful for future research to apply the same methodology to other civilizations to further prove the proposed theory. This research also coincides with current efforts to create a sustainable world in times when the climate is changing rapidly due to anthropogenic influences. Even though circumstances have changed considerably over time, this research could justify the possible connection between the current climate crisis and the fall of past civilizations. This could help decrease scepticism of the current climate crisis by illustrating the severe effect of (a relatively small) climate change in these historical civilisations.

To realise this aim, the following research question was constructed:

*To what extent Is there a connection between the fall of the Maya civilisation and the coinciding droughts (due to climate change)?*

To answer this question, this research will adopt the following structure:

- An explanation of the proposed theory and its concepts through a conceptual framework.
- The methodology that was used to carry out the research.
- The results of this research.
- A discussion where an interpretation of the results will be provided, together with the limitations and implications of this research.
- Lastly, the conclusion will provide a summary of the key findings and a conclusive answer to the research question.

# Theory and concepts

For this research to be comprehensive, it is important to establish what has already been identified through previous research as well as providing definitions to concepts that will be used in this study. These will form the foundation of this research. These concepts will focus on the mechanism at play between climate change and the fall of a civilization and will be visualized in a conceptual framework.

## Conceptual framework

The conceptual framework of this study regards the theory about how climate change can cause the downfall of a civilization. This theory is based on a combination of relations between concepts proposed in other research. To the authors knowledge, there is no paper that follows the exact same conceptual framework and thus a combination of these relationships will be used to create this new conceptual framework. This framework is illustrated in Figure 1. Due to climate change, a change in precipitation is induced, which leads to more droughts. (Medina-Elizalde & Rohling, 2012). Because of these droughts, crops that are partly dependent on precipitation, become more difficult to grow (Kuil et al., 2016). When the number of crops produced are less than what is needed to sustain the population, the population numbers would decrease due to migration or an increase in mortality rates. Another effect of these droughts is an unrest among the people, due to the failure of ceremonies that should provide sufficient rainfall according to Mayan rulers (Haug et al., 2003. Thus, there is a connection between the amount of precipitation and the political system of the Mayan people that was (partly) based on these ceremonies. When these droughts continue for multiple years, this affects the society as a whole and when a certain threshold is met, the society can collapse (Haug et al., 2003). An important aspect in this theory is the effect of crop production and population on forest land. A thriving society would need more resources for their increasing population. One way to accomplish this is to convert forest into crop land. The deforested land would further induce a drier climate and thus could to a societal collapse (Oglesby et al., 2010). This explains the connection between forest land and climate change in the conceptual framework.

It is important to acknowledge that there are other theories on how the Maya civilization could have collapsed. Examples are the erosion of soil, an epidemic or class-conflict (Kuil et al., 2016). It is possible that a combination of these factors resulted in the downfall of the Maya, however the goal of this research is to establish further to what extent this downfall can be attributed to climate change. Thus, even though these factors will be considered throughout the research, the focus will remain on climate change as the main variable.

The remainder of this chapter will focus on operationalizing the key concepts proposed in the conceptual framework, to ensure that the concepts can be measured during the data collection. Both qualitative and quantitative methods will be used during the data collection. That is why the concepts will be split into the sub-sections of "qualitative concepts" or "quantitative concepts". It is important to note that all concepts will be used for qualitative data collection to further prove the proposed theory, but only the "quantitative concepts" will also be used for quantitative data collection.

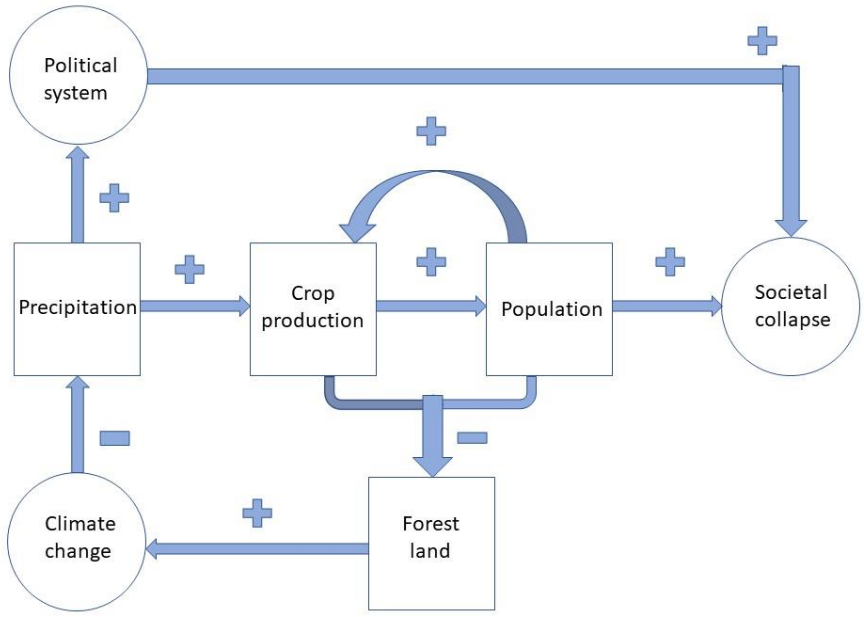


Figure 1: A conceptual framework that illustrates the theory that climate change can cause the downfall of a civilization. The term "climate change" only refers to the change in climate as explained in the proposed theory, thus more recurrent droughts. Here the "qualitative concepts" are illustrated in circles, while the "quantitative concepts" are illustrated in squares.

# Defining and operationalizing key concepts

## Qualitative concepts

### *Climate change:*

The following definition of climate change will be used: *"a change in the state of the climate that can be identified (e.g. using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. It refers to any change in climate over time, whether due to natural variability or as a result of human activity."* (UNFCCC, 2011, p. 1)

Most research states that climate change may have influenced the demise of the Maya civilization through extended periods of droughts, however it is not clear what mechanisms of the climate exactly caused these droughts. That is why this research will give an overview of the possible explanations given in research, as well as make an estimation on which of these is correct by looking at which option has the most evidence to back up the claims. The end goal was to provide a list with the possible changes in climate, together with the amount of research that was found that mentions these changes.

### *Societal collapse:*

The following definition will be used for societal collapse, as provided by Dunning et al. (2012, p. 3652): *"a fundamental and pronounced decline in sociopolitical complexity taking place within two or three generations"*. This concept, much as the concept of climate change, is more difficult to operationalize, since it is challenging to assign numbers to "sociopolitical complexity" while still being inclusive of all aspects of this concept. To determine whether the Mayan civilization collapsed, this research will provide an overview of papers that investigate whether a societal collapse of the Mayas was likely or not. Factors such as migration and extinction of the population were important here. When other factors emerged throughout this research, for example the resilience of the Maya population, these factors were also reviewed on whether they could have contributed to the proposed societal collapse of the Mayas. The goal here was to set a certain threshold under which a society is collapsed or not and whether the Maya civilization met this threshold. An illustration of such a threshold can be found in Figure 2. It is likely that the quantitative variable of size of population will be used here to determine this threshold.

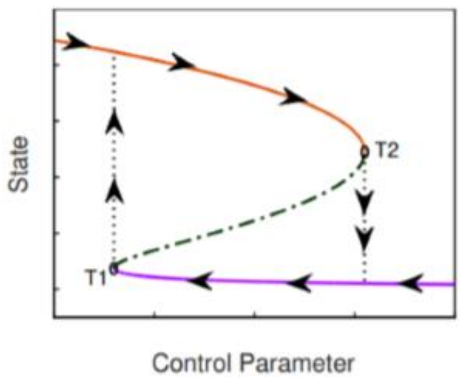


Figure 2: Illustration on how the collapse of a society("State") can be measured using a certain variable ("control parameter"). This Figure illustrates that after a certain threshold is met (T2), the society collapses. Retrieved from Liu et al. (2020)

## *Political system*

This research will solely focus on the part of the Mayan political system that concerns the proposed theory. In this theory, it is proposed that the Mayan society believed that their ceremonies were the deciding factor in whether their civilization would get enough water from precipitation to survive. When these ceremonies failed due to the recurrent droughts, social unrest became more pronounced in society and this factor could have been an important contribution to the societal collapse of the Mayan civilization (Haug et al., 2013). That is why this research analysed existing papers to see whether this proposition of the political system seems viable and whether there are still uncertainties on this part of the theory.

## Quantitative concepts

The following quantitative concepts will be measured: Precipitation, Crop production, Population, and Forest land. Table 1 provides an overview of these key concepts as well as how they will be measured.

### *Precipitation:*

In this research, precipitation will be defined as atmospheric moisture that condensates to form rainfall or snow. Quantitative data for precipitation was extracted from existing research that focused on the probability of droughts throughout the reign of the Mayan people. This data was extracted from the National Oceanic and Atmospheric Administration (NOAA) paleoclimatology database. By looking at the probability of droughts, the decrease of precipitation was established. This data was compared to the timing of the proposed societal collapse to see if these coincide with each other.

### *Population:*

Population decrease can come from deaths and less births, but also migration is seen as population decrease. This is an important distinction, since there is discussion on to what extent the Maya civilization migrated into other areas (Kuil et al., 2016). Population data was derived from the HYDE database. In the methodology section of this research the uncertainties of using this database will be explained. These population numbers will then be compared to the population numbers that can be found in literature.

### *Crop production:*

In this research, crop production will be measured in crop yields. No research has been found on crop production specifically for the Maya civilization. However, research by Turchin et al. (2020), applies a methodology to estimate crop yields in historical time periods. An altered version of their methodology will be applied in this research to fit the available data of the Maya era. First, it is important to establish the proportion of land that is used for agriculture throughout the era of the Maya empire. This was done by calculating the number of provisions that would be needed to sustain possible population counts for the Mayas. Secondly, the crop types that were favored by the Mayas were identified. This information will be used to determine how much food of a certain crop a person would need to have a sufficient calorie intake. These calculations resulted in the amount of crop land needed to sustain the population. This data was compared to estimated population and cropland sizes derived from HYDE to determine whether these results coincide with each other.

### *Forest land*

Forest land cover data will be derived from online databases. Research by Kaplan et al. (2010) used the HYDE database and their own calculations to estimate forest cover in historical times. This data was used to gather conclusions on forest land cover during the reign of the Maya empire. Unfortunately, the raw data used by Kaplan could not be found and thus no numbers can be assigned to these maps. Thus, estimations will be given based on the area of crop land derived from HYDE.

Table 1: Measurable concepts for quantitative data collection

| Key concepts | Measured variable | Unit |
|---|---|---|
| Precipitation | Probability of droughts of thriving Maya civilization vs. collapsed Maya civilization | % |
| Crop production | Crop yield of different crop types of thriving Maya civilization vs. collapsed Maya civilization | Kg/ha |
| Population | Size of population of thriving Maya civilization vs. collapsed Maya civilization | Individuals |
| Forest land | Size of land that is covered by forest of thriving Maya civilization vs. collapsed Maya civilization | Km^2 |

# Methodology

## Data collection

To answer the research question fully, the following methodological was applied. The aim of this research was to establish a cause-and-effect relationship between the fall of the Maya empire and a changing precipitation due to climate change. To accomplish this, both quantitative and qualitative data were required. The qualitative data was used to build a database of knowledge on the concepts derived from the conceptual framework. This database was used to test the consistency of proposed theory throughout research as well as determine the relationship between the key concepts. The quantitative data was used for the concepts “Crop production”, “Precipitation”, “Population” and “Forest land” to acquire more accurate data that illustrates the pattern proposed in the qualitative research.

For the qualitative data collection, a meta-analysis was used to systematically collect the data. The criteria on choosing the appropriate articles are important to ensure that the examined data were useful to answer the proposed research question. Firstly, it was preferred that data came from peer-reviewed articles to ensure credibility. It became throughout the research that grey literature could add insights to the discussion, thus an evaluation was made for each paper whether those insights outweigh the uncertainties associated with grey literature. Secondly, recent literature was preferred, to ensure that new data that had become available in recent years is not excluded. However, older research was not completely excluded since their findings could still provide useful insights. Thirdly, the data should be formed around the key concepts to ensure that it helps answer the research question. The data collection also focused on the connections between the key concepts, as well as the difference in these key concepts for a thriving maya civilization and a collapsed Maya civilization. For the quantitative concepts, online databases such as HYDE and NOAA were used as well as data derived from existing literature, as explained in the chapter "Theory and concepts". The HYDE is a database that is frequently used in research that estimates land use change in the past (Goldewijk, 2001; Goldewijk et al., 2010). It is important to recognize the fact that such databases often use estimates to determine their values, thus there are uncertainties in these data. However, these estimates can still provide valuable information and they are currently the most precise available option. For the crop land calculations, data was derived from FAOSTAT as well as from literature focused on nutritional values of different crops.

## Data analysis

After the literature research, the data has been analyzed. Both the quantitative and qualitative research were subjected to a deductive analysis using the proposed conceptual framework. A deductive analysis provides insights into the proposed theory and can better explain causal relationships than an inductive analysis would have.  For the qualitative data, the deductive analysis consisted of establishing patterns in data that explained the relations in the proposed conceptual framework. This is also called a thematic analysis. These themes were then coded into Excel to ensure that the data can be translated into theory in a scientific way. This resulted in an Excel sheet that indicates which paper mentions the different concepts in a way that is relevant to proof the proposed theory. With the use of different colors in Excel, a distinction was made between papers that contributed significantly to proving the proposed theory and papers that contributed only by either stating what has been established in other research or only contributed slightly in proving the proposed theory. An Example of the latter would be that a paper only researched part of the concept in question. Furthermore, a short mention of a concept that does not bring insight to the proposed theory was not included in the data analysis.

For the quantitative data analysis, multiple methods were used depending on the source of the data. The quantitative data collected through HYDE was collected in Notepad and then illustrated in ArcMap. Here, Notepad is used to ensure that the data is in the correct format for ArcMap.  ArcMap is frequently used to illustrate historical changes in landscape dynamics (Szilassi et al., 2006; Ali et al., 2011). The end goal here was to provide three maps for both the concepts "crop production" and "population", which illustrate the differences throughout the reign of the Mayan society. To accomplish this, HYDE data is used for the years 200 AD, 700 AD and 900 AD. After illustrating the HYDE data in ArcMap using the ASCII to Raster tool, an iso codes map was needed to create a second map which only contained the data for the research area in question. This was done manually by looking at the different iso codes for the Maya empire, and adding them together using the raster calculator. When the right area was established, the function "Zonal statistics as table" was used to calculate the total population and crop area for the research area. Finally, the iso codes map was used as a semi-transparent layer to highlight the Maya area. The data collected from the NOAA paleoclimatology database was first transcribed from Notepad to Excel, from which the relevant data was graphed using Excel graph tools. Data that was collected from other literature research did not need any further data analysis, since the writer of this paper did not have access to the raw data and thus could only use data that was already analyzed.

The FAOSTAT and literature data that were needed for the crop production calculations were analyzed using the following method: Research by Bronson (1966) stated that 94 persons per square mile of farmland could be sustained on a corn diet Equation 1 was used to calculate the area of crop field that would be needed to sustain the estimated population count. This was done for a population of 3,8 and 13 million people, as proposed by Haug et al., (2013). Different ratios of the most common crops were used to determine the effect of diet on the amount of crop areas, since there are still many uncertainties on what the exact diet was of the Mayan people (Bronson, 1966). The following ratios were used: 100 % maize, 75% maize & 12.5% beans & 12.5% squash and 50% maize & 25% beans & 25% squash. The food intake per person per day is based on an average diet of 2250 kcal and the calorie values of the different crops in respect to the proposed ratios. Crop yield data was derived from FAOSTAT for the countries Mexico and Guatemala, where the Mayan empire was located. Data was available for the years 1961-2019 for both countries. It is important to note that for data on the squash crop, FAOSTAT only had yield data available for the summarized category of Pumpkin, squash and gourds. Crop yield data derived from FAOSTAT is calculated on a yearly basis, thus it is important to keep the same timescale for the food intake (* 365). This resulted in a table with the crop land estimations for different population sizes and different diets.

*Equation 1: (Food intake per person per day (gram) * estimated population (in millions) * 365 (days))/ crop yield (gram/ km^2)*

## Justification methodology

By following this methodological approach, the writer was most likely to establish the relationships described in the conceptual framework and answer the research question. These methods were chosen through an examination of literature and their methods to ensure that the chosen methodology is applicable to answer the proposed research question. By creating a database of knowledge on the role of climate change on the fall of the Maya civilization, this research show whether different research is consistent with each other and whether the proposed theory is feasible. Furthermore, illustrating the differences in the two eras of the Mayas in ArcMap has provided a different perspective to further prove the proposed theory by illustrating the concepts in the conceptual framework. Special attention was given to avoid bias by continually challenge the assumption made in existing research, as well as possible assumptions of the writer of this research. A possible limitation was the uncertainty on the availability of data for the key concepts. However, when it became clear that a certain key concept does not contain enough data to make viable conclusions, as was the case for the concept “Forest land”, predictions could still be with the use of existing literature research.

# Results

This part of the research is designated to the results. First an overview is given, where the overall, concluding results are provided. Then, the structure of the results will follow the order of the concepts from the conceptual framework.

## Overview results

Overall, the results align with the proposed theory and the expectations set at the beginning of this research. Generally, the reviewed literature is consistent with each other. There is an overall agreement that climate change played a role in the demise of the Mayan people through the proposed theory. However, there are some exceptions, this is particularly true for the concepts “climate change” and “societal collapse”, where there are still some uncertainties. Furthermore, inconsistencies were found with HYDE data compared to what was found in literature. HYDE shows an overall trend of prosperity in the Maya civilization throughout the years, as if there was no collapse or societal decay of any degree. This does not align with what was found in literature. Moreover, estimations on population count and crop land of HYDE do not coincide with what is found in literature. HYDE has an overall lower estimate for both concepts.

## Results for each concept

This part of the results will provide a combination of qualitative and quantitative results, following the structure of the conceptual framework.

### Climate change

All papers in the meta-analysis that mentioned climate change in a significant way for the proposed theory agreed on the fact that climate change was an important factor in the demise of the Mayas. It is proposed that climate change caused the droughts, however, there is uncertainty on the exact mechanism that caused this change in the climate. Possible factors are variability in the internal climate system (Hunt et al., 2005), displacement of the ITCZ (Haug et al., 2013) and a minimum in solar insolation (Lucero, 2002). The latter two have been connected to each other by Gill et al. (2007), which explains that the minimum in solar radiation caused the displacement of the ITCZ. However, Gill et al also stated that this was not completely proven.

## Societal collapse

Research mostly agrees on the fact that there was a societal collapse of the Mayan civilization. There is also agreement that the collapse occurred in the Southern area first and the Northern areas were affected later. The following timeline of collapse was proposed by Haug et al. (2013): In the Pre-Classic period (before 150 A.D.) the Mayan civilization thrived and started to build their cities. During 150-250 AD, the first abandonment was recorded, but the civilization was soon reestablished duing the Classic period (250 A.D. to 750 A.D.). This period ended with the Terminal Classic Collapse (750 A.D. to 950 A.D.), where cities were permanently abandoned.

There is uncertainty however, to what extent the situation of the Mayas can be called a complete societal collapse. Both Lucero (2002) and Haug et al. (2013) suggest that smaller cities were less affected, and Lucero (2002) adds that higher altitudes were mainly affected by the droughts. Gill et al (2007) proposed that the collapse occurred in different stages throughout the years. Dunning et al. (2011) is the only paper that questions whether the situation of the Mayas can certainly be called a collapse. Dunning et al. argues that the abandonment had a time span of 125 years, and this would suggest a societal transition instead of a societal collapse. Besides from the size of the settlement, the location is of importance as well to determine the extent of the collapse. Coastline settlements were more adaptable and were more independent in their water accessibility, thus the possibility of a collapse would have been less likely (Dunning et al., 2011).

## Political system

There is a clear connection in literature that the political system of the Mayas contributed to the societal collapse. The political system of the Mayas was based on the believe of the common people that their rulers had connections with the gods (Mott, 2012). The rulers would then ensure that there was enough rainfall to sustain the population. When this failed due to the recurrent drought, a societal unrest unfolded. Both Haug et al. (2013) and Lucero (2002) state that smaller cities or regions were less affected since there was less artificial water control through Mayan rulers there. The meta-analysis could not quantify to what extent this societal unrest led to the proposed societal collapse, since only 4/13 papers made conclusions on this concept.

## Precipitation

Generally, research agrees on the fact that during the Terminal Classic period, there were more droughts than during the Classic period, which was known for its abundance of rain. Thus, the timing of the Mayan collapse and the droughts coincide. There are. However, some details that are highlighted in some paper and not in others. The Mayan civilization was located at the edge of the tropical rainfall zone, which meant that it was more susceptible for changes in this rainfall zone and thus more susceptible for droughts (Gill et al., 2007). Mott (2012) states that Mayan cities were heavily reliant on the abundance of rain that during the rise of the empire. Thus, when droughts became more prominent, the Mayas were not prepared which made their downfall even worse. Medina-Elizalde & Rohling, (2012) also highlights that Maya area is likely highly sensitive to changes in precipitation.

Furthermore, the availability of quantitative data further proves the statements that were found in the meta-analysis. This data is illustrated in Figure 3, where the probability of the occurrence of droughts is displayed. Here, the probability of drought is higher in the years that the proposed societal collapse would have happened. The data also coincides with the timeline as proposed by Haug et al. (2013). Further evidence of droughts can be found in Figure 4, which illustrated the deviation in rainfall from 800 to 950 AD compared to previous years. Here, the largest difference was found in the northern part of Mayan civilization. This illustrates that this was the area where most of the major droughts occurred. No illustrations or raw data were found of the time period before this, so there is no proof whether these rainfall anomalies coincide with literature that states that the southern part was hit first by the droughts.

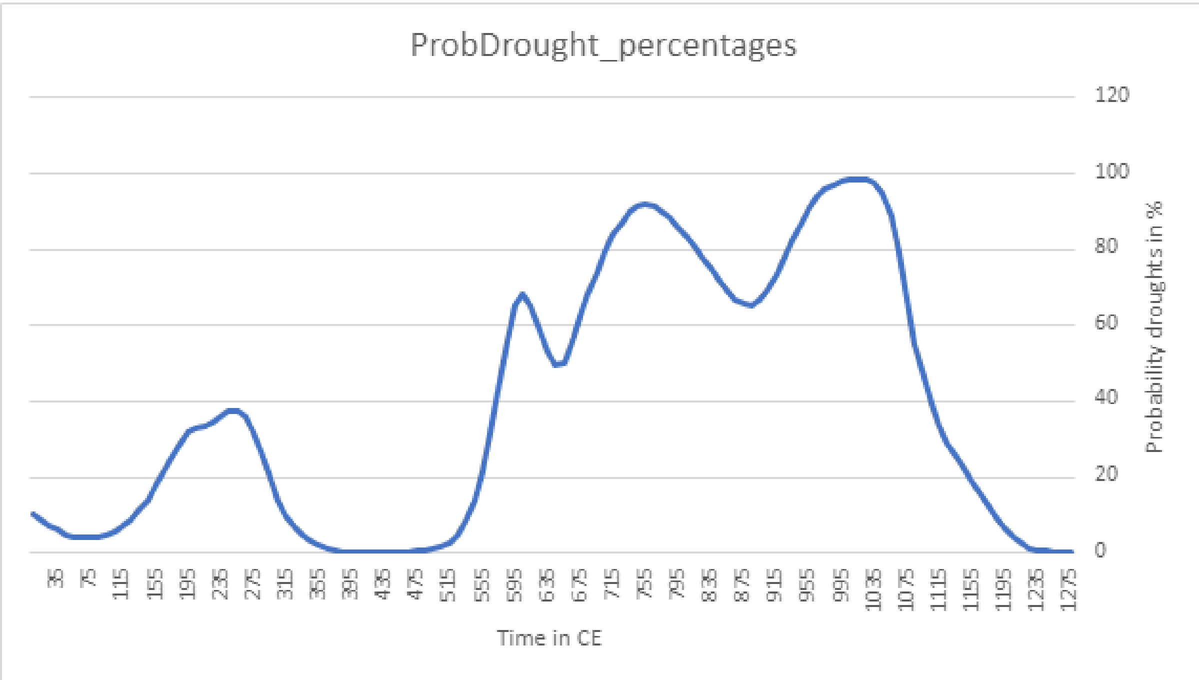


Figure 3: Graph that illustrates the probability of droughts using data from Lake Chichancanab, Mexico. Data derived from (National Centers for Environmental Information (NCEI), n.d.)

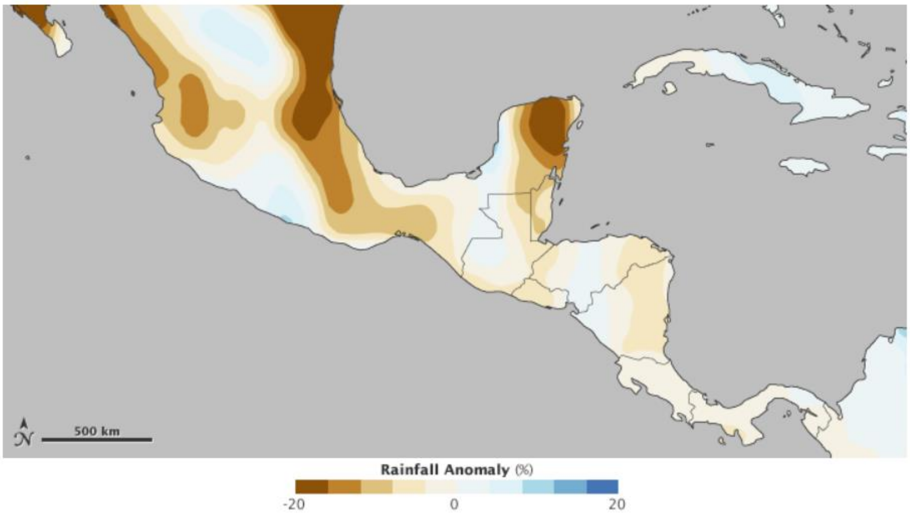


Figure 4: Map that illustrates rainfall anomaly in Maya empire in the year 800 – 950 AD. Derived from (Allen, n.d.)

## Population

There are indifferences in literature on what happened exactly to the population (numbers) of the Mayas. It is clear throughout literature that population numbers increased during the Classic period and none of the papers in the meta-analysis suggested anything else. After the proposed societal collapse, it is not completely clear what happened to the Mayan population. Some papers suggested that people abandoned their cities for the northern coastal areas and did not return for a variety of reasons. Some of these reasons include the rise of economic opportunities elsewhere (Lucero, 2002), maintenance of rainfall capture mechanism and the believe that the lands were ill-fortuned (Dunning et al., 2011). Another reason suggested by Hunt & Elliot is that drought-related diseases occurred, which made people wary for returning to these disease-ridden cities. It could also be possible that the population changed their building techniques which do not show in archaeological records (Lucero,2002). It is interesting to note that only Gill et al. (2007) and Kuil et al. (2016) suggested an actual decrease of population numbers, while others only discussed migration to other areas of the land.

When comparing the literature findings to HYDE data, which are illustrated in Figure 5, 6 and 7, it becomes evident that they do not align with each other. While literature suggests a collapse to some extent around 700-700A.D., the population in the HYDE data continues to grow even in 900 A.D. From 200 to 700 A.D., there is an increase from 684.890 to 936.636 people, which is an increase of around 37% (7.4% each 100 years). From 700 A.D. to 900 A.D., the population frows from 936.636 to 1.249.197 people, which is an increase of around 34% (17% for each 100 years) Even though only 1 paper suggests a population decrease, there are none who imply a continuing population increase.

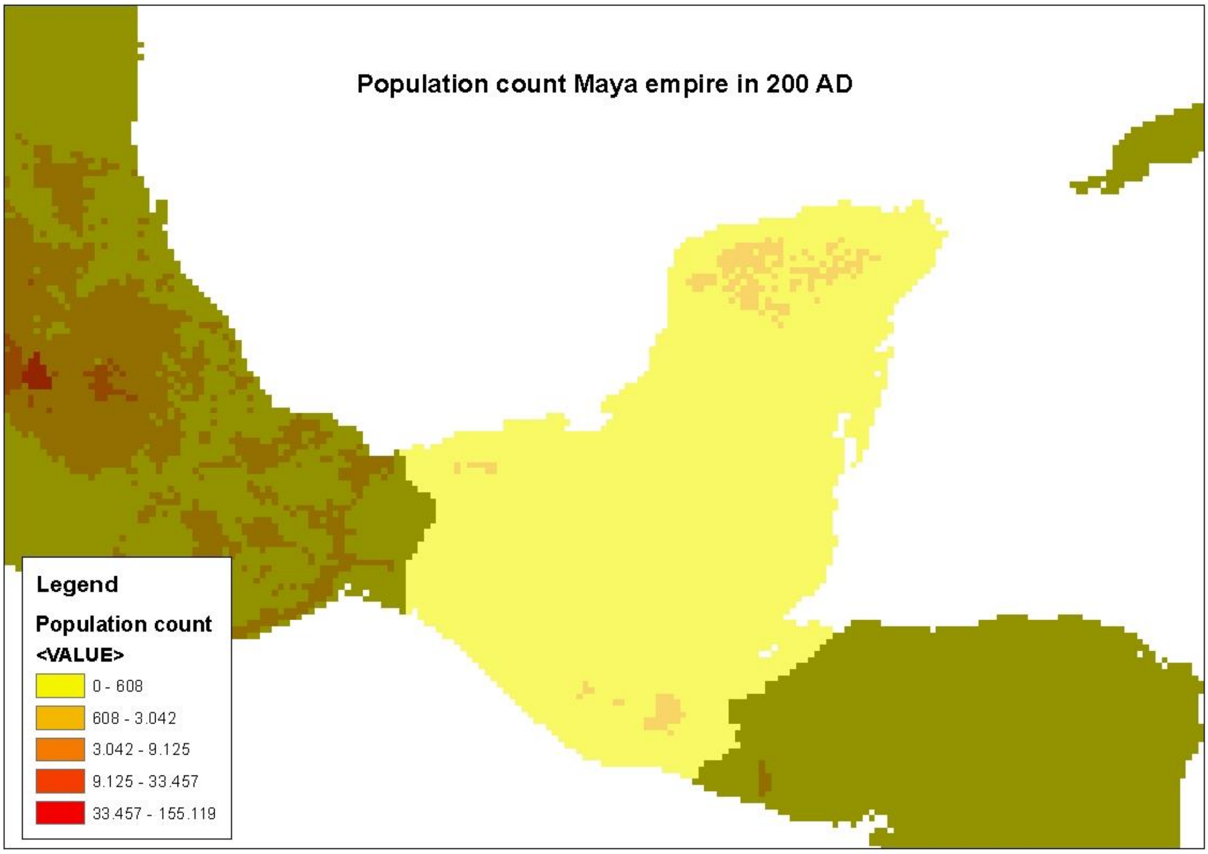


Figure 5: Population counts throughout the Mayan empire in 200 AD. The total population amounts to 684.890 people. Data derived from the HYDE database.

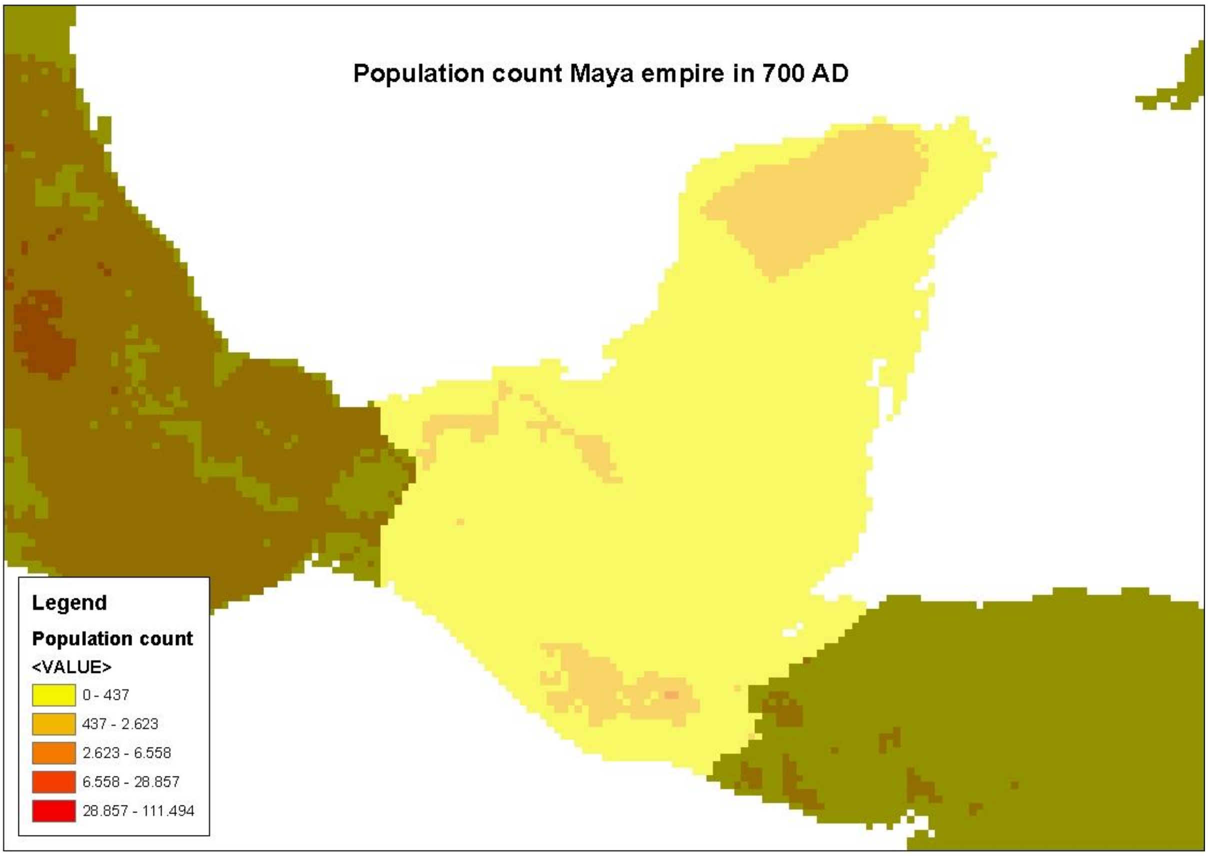


Figure 6: Population counts throughout the Mayan empire in 700 AD. The total population amounts to 936.636 people. Data derived from the HYDE database.

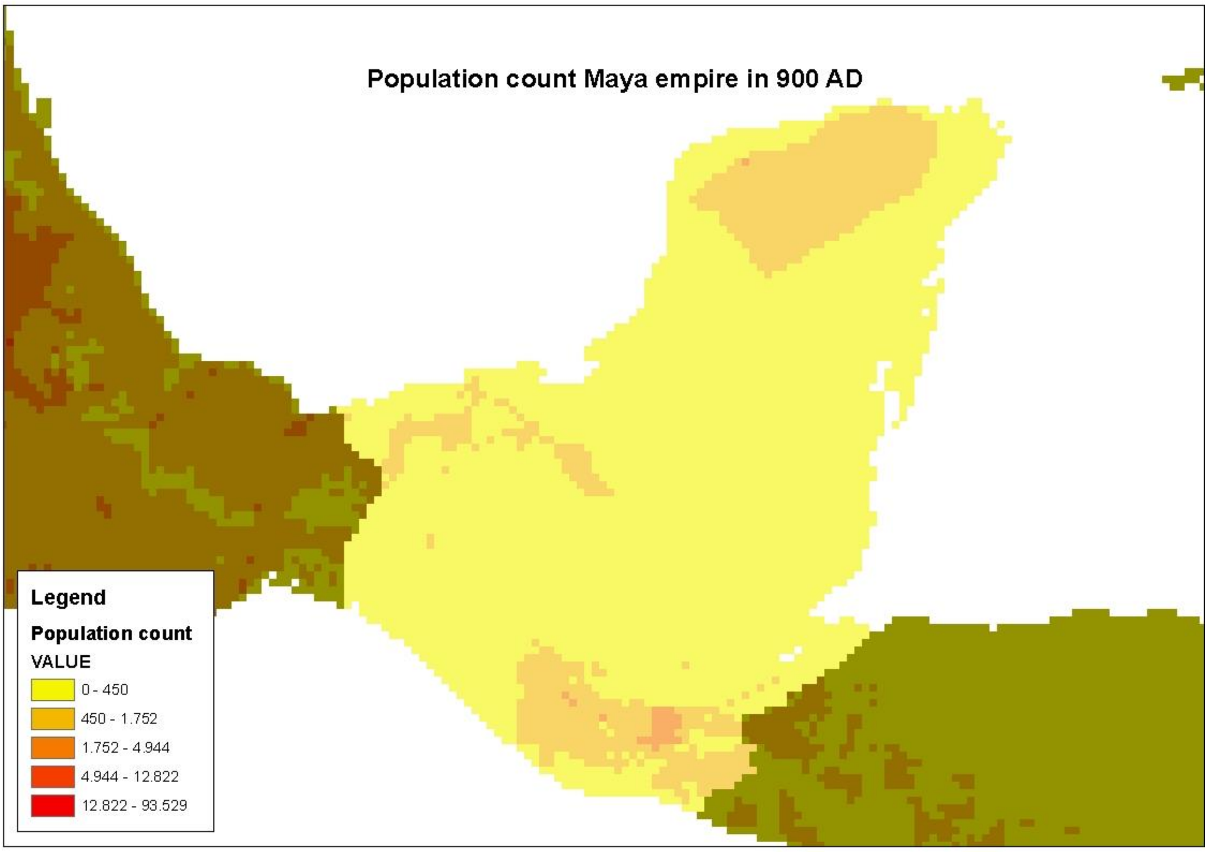


Figure 7: Population counts throughout the Mayan empire in 900 AD. The total population amounts to 1.249.917 people. Data derived from the HYDE database.

## Crop production

Found Literature has sketched there was a increase of crop land at the expense of forest land. This resulted in an expansion of crop land and this led to soil depletion(Lucero, 2002; Dunning et al., 2011). According to Gill et al., 2007, there is evidence that agricultural activity dropped steeply after 750 AD. This coincides with the timing of the proposed societal collapse, and thus supports the proposed theory. Moreover, multiple sources report that the Mayas practiced milpa agriculture or also known as slash-and-burn agriculture, which already uses extensive amount of crop land to produce food (Bronson, 1966; White & Schwarcz,1989). The agricultural system of the Mayas was also reliant on an excessive amount of rainfall (Bronson, 1966) and thus was not able to function when droughts became prominent (White & Schwarz, 1989)

However, what was found in literature does not completely line up with HYDE. This data is illustrated in Figure 8, 9 and 10. An increase of crop land can indeed be observed between 200 – 700 AD. Total crop land area goes from being 4.940 km^2 to 7.590 km^2, which is an increase of around 54 % (10,8% per 100 years) According to literature, this would be the era where the Mayas flourished and thus an increase of crop land makes sense to sustain the growing population. However, a relatively bigger increase of crop land is illustrated in the year 900 A.D. Total crop land area goes from 7.590 km^2 to 10.573 km^2, which is an increase of around 39% (19,5 % per 100 years) According to the literature, society would have collapsed by then and this does not coincide with an increase of cropland.

Lastly, Table 2 was created to determine crop land area following FAOSTAT data and Equation 1. This table shows the effect of different population sizes on the amount of crop land that is needed. Here it can be seen that using the calculations (See Annex C), the amount of crop land is significantly larger than crop land data derived from HYDE. Even when considering that HYDE has smaller population estimates, the difference is relatively much larger. When taking into account the total area of the Mayan empire, there would simply not be enough room to create the calculated number of crops.

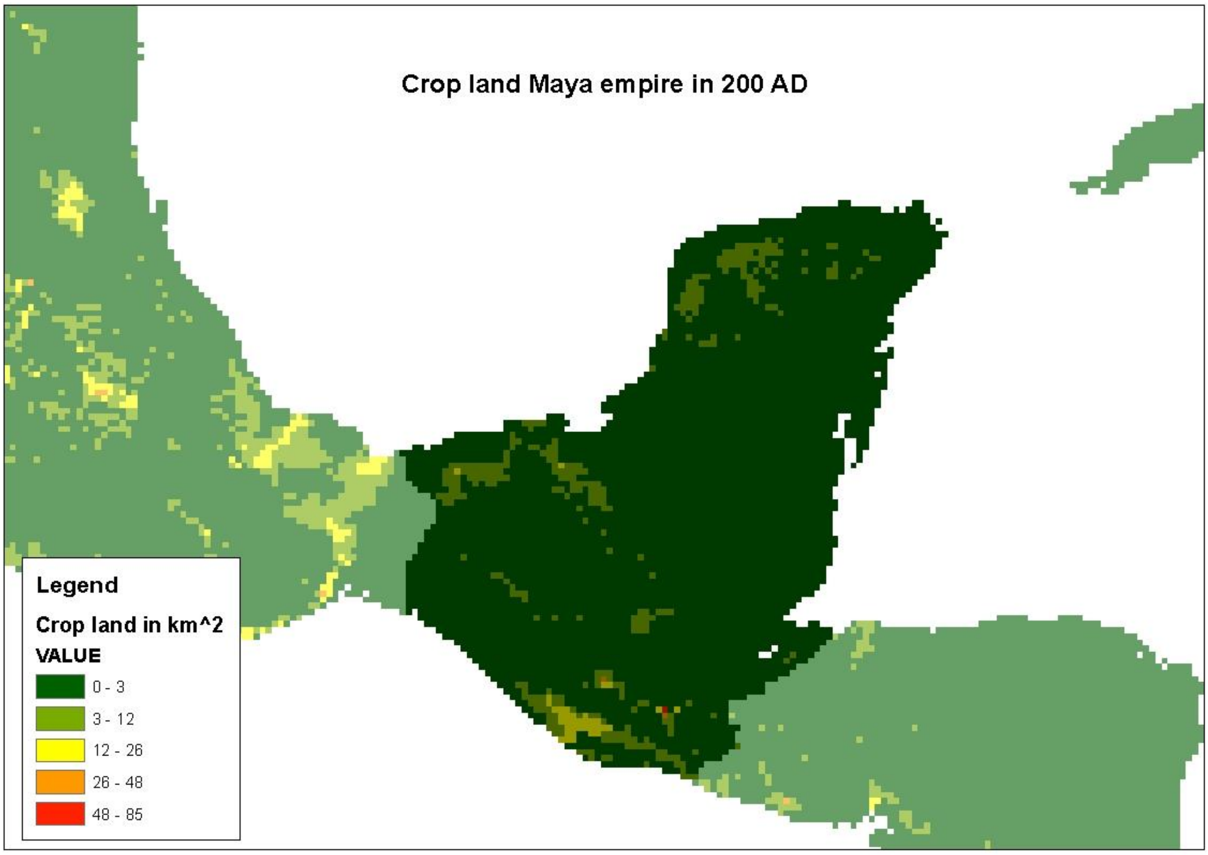


Figure 8: Crop land throughout the Mayan empire in 200 AD. The total amount of crop land amounts to 4940 km^2. Data derived from the HYDE database.

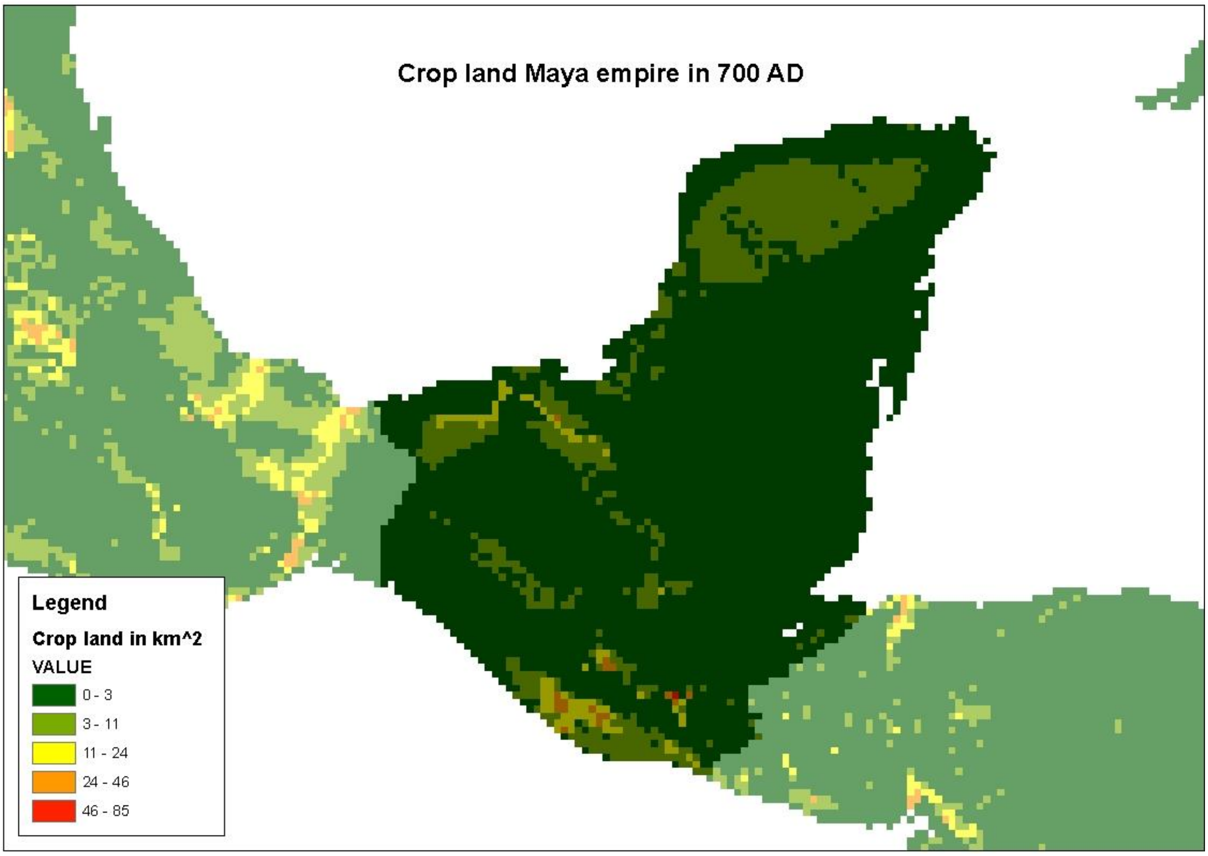


Figure 9: Crop land throughout the Mayan empire in 700 AD. The total amount of crop land amounts to 7590 km^2. Data derived from the HYDE database.

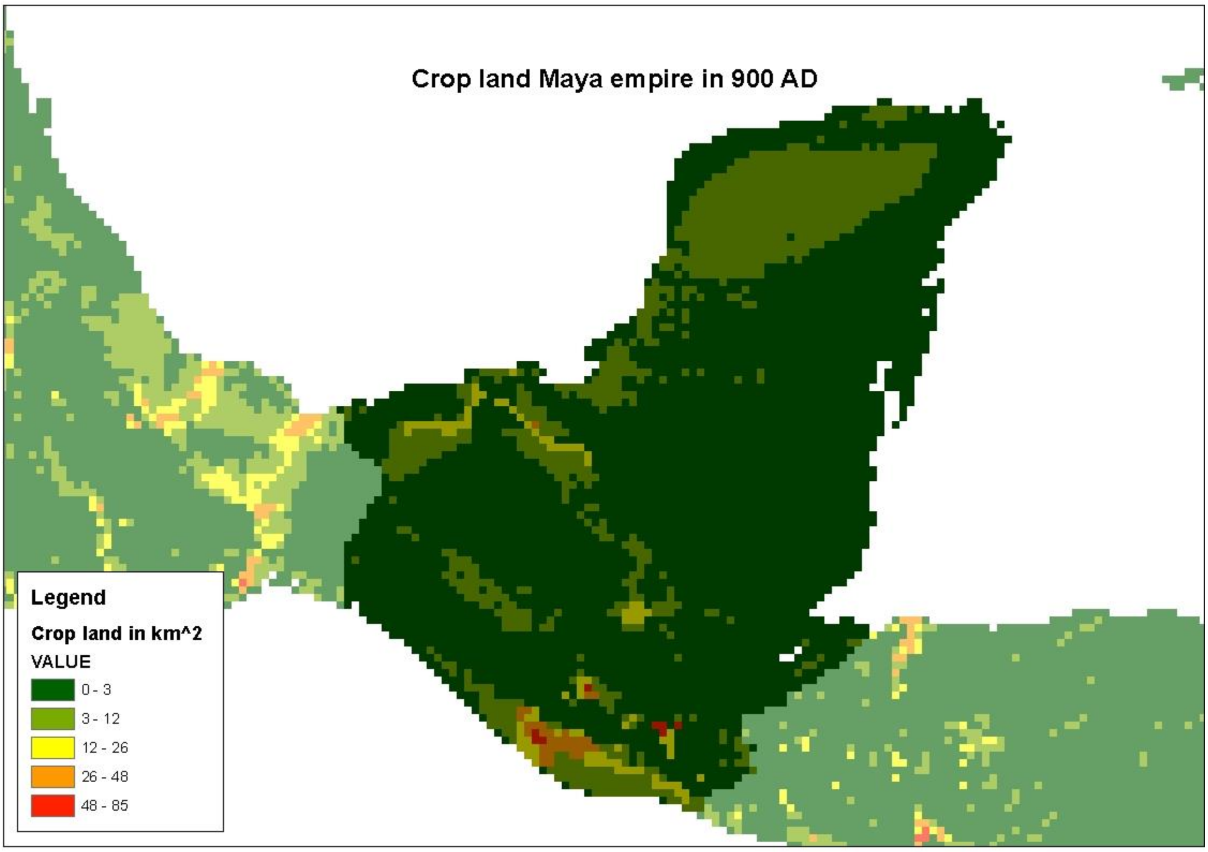


Figure 10: Crop land throughout the Mayan empire in 900 AD. The total amount of crop land amounts to 10573 km^2

Table 2: An overview of crop land (km^2) in the Mayan empire, following different population counts and different types of diet. These numbers are based on calcultations using Equation 1.

| Estimated population | Maize diet (Bronson, 1966) | Maize diet (FAOSTAT) | Estimated crop land in km ^2<br>75% Maize (Bronson) 12.5% squash (FAOSTAT) 12.5% beans (FAOSTAT) | 50% Maize (Bronson) 25% beans (FAOSTAT) 25% squash (FAOSTAT) |
|---|---|---|---|---|
| 3 million | 82.873 | 35.126.973 | 20.448.903 | 40.814.932 |
| 8 million | 220.994 | 93.671.927 | 54.530.759 | 75.838.245 |
| 13 million | 359.116 | 175.634.864 | 88.611.890 | 176.864.664 |

## Forest land

Even though only 4/13 papers discussed the amount of forest land there is a consensus in papers that the increase of crop production led to deforestation. The deforestation then led to droughts, which were further amplified by climate change according to Mott (2012) and Dunning et al. (2011) On the other hand, it is suggested by Cook et al. (2012) that the deforestation induced a change in the climate on its own. Thus, literature is not certain to what extent the droughts were caused by deforestation or by climate change. Cook et al. (2012) suggest that a 15-30% reduction in summer precipitation was induced due to deforestation, while Mott (2012) implies an annual 5-15% decrease. Stromberg (2012) further suggests that a total of 60% of the droughts were caused by deforestation. Dunning et al (2011) and Stromberg (2012) highlights that deforestation also affected the regional environment through erosion and soil fertility.

Research by Kaplan et al. (2011) created the graph in Figure 11, which displays the natural vegetation fraction in the Mayan area. Here it can be seen that the vegetations fraction is lower at the southern and northern locations of the Maya empire, while it is higher in the middle area. Unfortunately, due to lack of raw data no numbers can be assigned to Figure 11. However, since it is speculated that the majority of the increase of crop land was at the expense of forest land, these numbers can be used to make estimations on the decrease of crop land. Crop land area in HYDE went from 4.940 km^2 to 10.573 km^2, which is an increase of 5.633 km^2. Thus, it can be speculated that according to HYDE data, forest land decreased by 5.633 km^2.

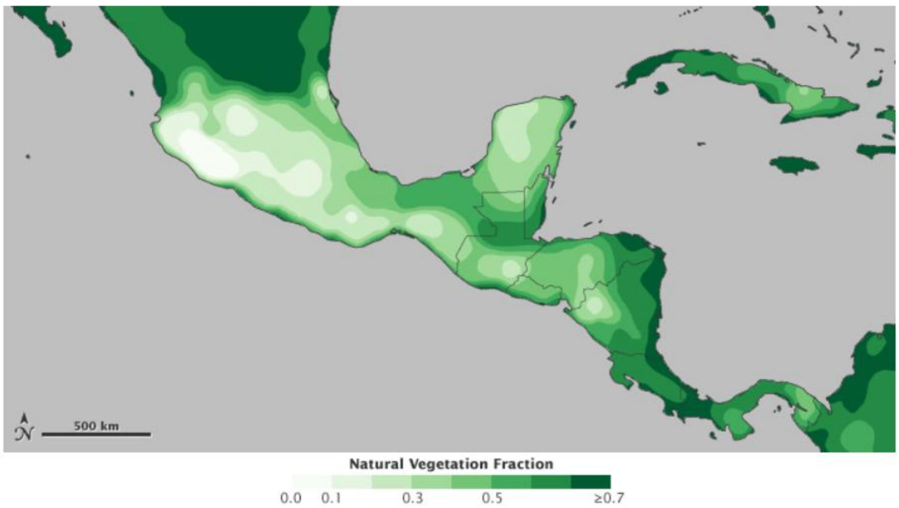


Figure 11: Map that illustrates natural vegetation fraction in Maya empire in the year 800 – 950 AD. Derived from (Allen, n.d.)

# Discussion

Overall, the findings coincide with the proposed theory and conceptual framework. None of the findings contradicted the proposed theory, however there are some aspects that are not completely clear yet. This part of the paper is therefore dedicated to discussing this research, using the following structure: First an interpretation is given of the results, following the structure of the conceptual framework. Then the limitations of this research are discussed, to accurately provide a picture of what can(not) be concluded from this research. Lastly, the theoretical and societal implications of this research are given to acknowledge which new insights this research has contributed to science, as well as any recommendations for future research.

## Discussion on each concept

Even though research seems to agree on the fact that climate change caused the demise of the Mayas to some extent, the causing mechanism of this climate change is not certain. Insights from Gill et al. (2007) do provide an interesting angle. This paper explains the possible connection between a minimum in solar radiation and a displacement of the ITCZ and even though this has not been completely proven, it could explain why evidence in literature can be found for both factors (Haug et al., 2013; Lucero, 2002). It is possible that a combination of all the mentioned mechanisms caused the climate change, however the most evidence was found for both the minimum in solar radiation and the displacement of the ITCZ. Thus, together with the insights of Gill et al. (2007), this research concludes that a combination of these two were likely the cause of the climate change.

The concept "societal collapse" is the most uncertain throughout the theory. Even though many papers suggest a collapse to a certain extent, only one paper in the meta-analysis explained the complexity behind a societal collapse and the importance of resilience in this process. Papers such as Cook et al. (2012) and Kuil et al. (2016) state that there was a collapse of the Mayan society, but do not explain why this is the case. It seems that papers do not follow any threshold to determine whether the Mayan civilization collapsed. Thus, this research failed to establish the threshold to determine whether the Mayan society collapsed and thus it is difficult to determine whether it is certain that the Mayan society collapsed. However, there is a consensus in research that the Mayan society collapsed, especially in larger settlements. This also coincides with what was found for the concept "political system", where cities endured a collapse due to the societal unrest. Thus, this paper argues that the larger settlements underwent a societal collapse, while smaller ones did not so severely. As highlighted by Dunning et al. (2011) spatial relevance is important here and stating that the entire Mayan society collapsed does not seem to be true. Especially considering that there are still Mayan people living in the same area.

The concept of the political system of the Mayas was only discussed in a couple of papers but it could be an important part in the theory. It explains how larger cities were most affected due to societal unrest. Societal unrest has also been an important factor in the demise of other civilizations, such as the Ming dynasty (Zheng et al., 2014) and other Chinese civilizations (Zhang et al., 2005). The latter article argues the importance of a stable and favorable climate for limiting societal unrest. This seems to illustrate that the (failed) political system of the Mayas and the societal unrest it produced was an important factor in the demise of the Mayas, even though it seems often overlooked in research.

Research seems to agree that droughts were more prominent during the collapse of the Mayan people and thus that the timing overlaps. It also became clear that there was an abundance of precipitation during the rise of the Mayan society, and that the people heavily relied on this fact. The only uncertainty found in literature here is related to Figure 4, where it seems that the droughts would have been mainly in the north and not in the south as proposed in literature. However, only one timeslot was found in this research, so no viable conclusion can be drawn from this. A fascinating aspect of this concept is the connection between the prosperity of a society and the amount of precipitation. It seems that the abundance of rain was one of the reasons that the Mayas were able to thrive and build their society, while it was also part of the reason their society failed in the end.

There are some uncertainties for the concept “population”. Even though research seems to agree that population numbers increased during the Classic period, it is not certain what exactly happened after the collapse. Literature seems to agree that the type of agriculture practiced by the Mayas needed an excessive amount of rainfall to function and thus the increase of droughts would result in the failure of the agricultural system to some extent. So, it would make sense that this would result in a population decrease, since not enough food could be produced to sustain the population. However, only one paper in the meta-analysis suggests a population decrease, while other papers only mention the evidence for migration of the population. It is possible that a combination of these options is true, but further research is needed to investigate what exactly happened to the population of the Mayas. Furthermore, HYDE data does not seem to agree with literature on both the total population count and the collapse. During the time of the collapse, HYDE data shows an even further percentual increase from 7,4% to 17% per 100 years. This does not align with the found literature. It could be that HYDE did not yet focus on the specific Maya situation and assumed a general trend of growth which can be observed throughout the world in HYDE data.

There is a consensus in research that the Mayan agricultural system was heavily reliant on an abundance of rainfall and that is why crop production failed during the increase of droughts. However, there are some uncertainties in the calculations made. The crop production calculations following FAOSTAT data seem to be out of proportion compared to the total available land that the Mayas had access to. They also seem out of proportion when comparing it to the calculations derived from Bronson (1966). There are multiple explanations for this, it could be that the Mayan people ate less than an average of 2250 kcal/day, or that animal protein had a larger contribution to the calorie intake. Another interesting theory could be that the Mayan people got most of their food through trade with the Mexicans, who had a great amount of crop land according to HYDE. The calculations based on the information derived from FAOSTAT do not seem to reflect reality, however, the calculations do illustrate the fact that there are still many things unknown about the situation of the Mayas and that is one of the reasons it is difficult to determine to what extent the society collapsed. The estimated population counts of 3, 8 and 13 million show there is a large difference in cropland needed to sustain such different population counts and these would all result in a different impact on the environment. The uncertainty of the diet of the Mayas also had an impact on the total crop land, this uncertainty needs to be eradicated to bring more certainty in the proposed theory.

Literature seems to agree that the increase of crop production to sustain the growing population lead to more deforestation. This deforestation led to a decrease of precipitation and thus more droughts in the Mayan empire. It is not certain to what extent the droughts were caused by deforestation and which caused by a change in the climate. However, it is likely that they both played an important role since both processes occurred at the same time they amplified each other, making the droughts worse.

Overall, it seems that the entire conceptual framework is important in trying to explain the demise of the Mayas. Due to all the connections of the concepts, it is likely that the severity of the collapse, especially in large settlements, cannot be explained without these links. The Mayas has shown resilience through its long existence before the collapse (Nations & Nigh, 1980), so one could argue that if only one aspect of theory was threatening the Mayas, it would have been likely that the Mayas would have solved the issue. It does seem that the climate is the overarching factor that set the collapse in motion. First, the favorable climate made the Mayas thrive, which resulted in an increase of population and an increasing need for food. This resulted in deforestation, which led to a change in the local climate, making it drier. During this time a climate change was induced, which was likely caused by a minimum in solar radiation which led to a displacement of the ITCZ. This then caused the demise of the Mayas through the proposed conceptual framework.

## Implications and limitations

The proposed theory shows the importance of a stable climate for a society to thrive, and the conceptual framework shows the many consequences that a change in the climate could entail through many aspects of a society. Even though not everything is certain in the proposed theory, it can be said that the climate had a major impact on the Mayan society, even though the proposed changes in precipitation were not that severe (Medina-Elizalde & Rohling, 2012), especially compared to the climate change our society is facing now or will face in the future. Thus, one could argue that our society can learn from past civilizations. There are similarities between both situations, especially when looking at the current deforestation rates and the population growth of the past decades (Pahari & Murai, 1999). However, it is also important to acknowledge that these similarities do not entail that our society is condemned. According to Degroot et al. (2021), there are also many cases in which past societies survived, or even thrived, on changes in the climate and. Degroot et al. argues that many papers focus only on the demise of past societies, and not the resilience they have shown in the past. Furthermore, spatial variability is often ignored in research and these aspects create a skewed image in which societies are condemned to fail when facing climate change, however this is not the case. This research has a further scientific relevance, by showing the use of a conceptual framework to illustrate the important connections between the causes of the fall of society and the fall itself. This research can be used to look at other societies and their possible demise, using alterations for the specific situation.

There are, however, some limitations to this research. There are still some uncertainties in paleoclimatic data, and it is not certain whether the current estimations made in research are true (Kenneth et al., 2012). As explained before, data on exact population counts or crop land is often unavailable, and many databases are based on estimations. These estimations make it difficult to confirm the theory and this was especially difficult for the concept "societal collapse". However, there still was a consensus in papers and in archaeological evidence that the Mayan society collapsed to some extent, especially in larger settlements. Furthermore, the meta-analysis only contained a total of 13 papers, since many concepts were involved that needed to be studied. Thus, it could be the case that some data is missing. However, since there were no contradictions in the meta-analysis, it is expected that these would not be found in other research. Out of the 13 papers, two were specifically selected for the concept "crop land" and these two papers only provide information on that one concept. This could give a skewed image when looking at which of the concepts I mentioned most often in this research.

## Conclusion

To summarize the findings of this research; this research was carried out with the use of a meta-analysis as well as a quantitative data analysis. During this analysis, it became evident that the proposed theory is overall consistent throughout research. Even though there are still some uncertainties for some concepts, mainly for “climate change”, “societal collapse” and “population”, none of the papers contradicted the theory in any major way. The goal of this research was to answer the following research question: *To what extent Is there a connection between the fall of the Maya civilisation and the coinciding droughts (due to climate change)?* The answer to this question would be that according to the proposed theory, the climate would have been the all-deciding factor that set the collapse in motion. The favorable climate during 200-700 AD made the Mayan a thriving civilization that was dependent on such a climate to survive. This likely led to the population increase and a greater demand for food and this resulted in deforestation. This deforestation led to a decrease in precipitation, which was further amplified by climate change. This climate change was likely caused by a displacement of the ITCZ due to a minimum of solar insolation. Due to both the deforestation and climate change, drought became more frequent, and this had an impact on the Mayas through the proposed theory which ended in a societal collapse to some extent. Thus, even though the droughts that were caused by climate change are not the only concept that played a part in the demise of the Mayas, it is the concept that influenced all the other concepts.

This research shows the importance of a favorable and stable climate for a society to thrive, but it is also important to consider the resilience past societies has shown. This means that even though we can learn from these fallen societies to prevent the downfall of our current society, we can also learn that societies are resilient and that a change in the climate does not have to entail the end of a society.

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## Annex A: Qualitative data analysis

Table 3: An overview of the meta-analysis that illustrates which paper supports which concept from the conceptual framework, in a way that is relevant for the proposed theory.

| | | | | Qualitative data collection | | | |
|---|---|---|---|---|---|---|---|
| | Climate change | Societal collapse | Precipitation | Crop production | Population | Forest land | Political system |
| Haug et al. 2013 | | | | | | | |
| Lucero 2002 | | | | | | | |
| Mott, 2012 | | | | | | | |
| Stromberg, 2012 | | | | | | | |
| Hodell et al., 1995 | | | | | | | |
| Medina-Elizalde & Rohling, 2012 | | | | | | | |
| Dunning et al., 2011 | | | | | | | |
| Bronson 1966 | | | | | | | |
| White & Schwarcz | | | | | | | |
| Kuil et al., 2016 | | | | | | | |
| Cook et al. 2012 | | | | | | | |
| Hunt et al., 2005 | | | | | | | |
| Richardson et al., 2007 | | | | | | | |

# Annex B: Calculations Crop area

| | Yield average in g/km^2 (derived from FAOSTAT data) | Nutritional value in Kcal/100 g |
|---|---|---|
| Beans | 6894,2 | 315 (derived from Voedingscentrum (n.d.)) |
| Squash | 124.079,3 | 40 (derived from Nutrition data (n.d.)) |
| Maize | 19.126,0 | 365 (derived from Nuss & Tanumihardjo (2010)) |