The Origin of Agriculture in the Peiligang Culture: An Agent-based Modeling Approach

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Abstract

The emergence of agriculture played an important role in human history as it allowed people to move from a nomadic to a sedentary life. This not only provided abundant food, but also sufficient numbers of non-cultivating specialists, which are necessary conditions for the rise of civilization. However, questions about how and why agriculture originated have remained controversial. This paper explores the origin hypotheses of agriculture, using the canonical theory of social complexity as a framework to the transition from hunter-gatherer to agricultural societies in the region of the Peiligang culture in China based on existing literature, and develops an agent-based model to simulate the transition process. The model assumes that the combination of population growth and gaining knowledge on plants drove the transition to agriculture. Results show that based on the basic hypotheses and assumptions, the model is able to generate the key phases that are identical with the existing literatures.

Keywords: Agent-based models, GIS, Neolithic Revolution, Peiligang

1. Introduction

The origin of agriculture played an important role in human history, as it provided the foundation for the evolution of complex societies. Many scholars believe that the agricultural way of life provided abundant food and sedentarization, which supported high population and sufficient numbers of non-cultivating specialists that gave rise to the first civilizations. Gupta (2004) suggests that the emergence of civilization is generally associated with the Neolithic, or Agricultural Revolution. Out of agriculture, cities and civilizations grew.

However, the question about how and why agriculture originated has remained a much debated topic. There are many different hypotheses that attempt to explain how and why people adopted to agriculture as a new way of producing food. The Oasis Theory suggests that as the climate became drier, human beings had to settle near an oasis, where they were forced into close association with animals which were then domesticated together with planting of seeds (Childe et al., 1928). However, this theory is not supported by the climate data, which show that the region was getting wetter rather than drier (Scarre, 2005). Demographic theories suggest that agriculture emerged because increasingly sedentary population exceeded the carrying capacity of the local environment, which required more food than could be gathered (Sauer, 1952; Lewis, 1968). The Neolithic Revolution occurred in various locations in the world between 8,000 and 5,000 BCE was the wide-scale transition of many human cultures from a lifestyle of hunting and gathering to one of agriculture and settlement, allowing the ability to handle an increasingly larger population (Bocquet-Appel, 2011). Although the origin theories are different and controversial, all theories agree that fully charged ecological interaction provided the full knowledge of plants that was necessary for domesticating plants (Loewe and Shaughnessy, 1999).

All the hypotheses about the origin of agriculture seem to make sense in theory. It is very likely that the combination of more than one of the hypotheses led to the result. Although there is no way to make sure which hypotheses are correct, one way to test these hypothesis is through simulation. A simulation model using the origin hypotheses will help us better understand how and why agriculture originated. Therefore, one approach to study the emergence of agriculture is by agent-based modeling (ABM).

2. Background

Many studies show that agriculture and civilization was found in China about 8000 years ago, in the region of the Peiligang culture, a group of Neolithic communities near the Middle Yellow River basin in Henan Province, China. Figure 1 shows the area of the Peiligang culture. The Yellow River basin appears to have been where foxtail millet (Setaria italica) and broomcorn millet (Panicum miliaceum) were domesticated approximately 8,000 years ago (Fuller, 2007). According to archaeological excavations and studies, there is about 0.8 to 1.5 square meters of carbonized millet particles in the Xinzheng village, a village of the Peiligang culture (Wang, 1984). Carbonized millet particles were also found in the Ding village in the Xuchang village in a half-underground house (Wu, 1983). The carbonized millet particles in Ding village, another village of Peiligang culture, are identified as spring millet (Li, 1984). Foxtail millet is an annual grass, and its sowing time is usually in late April to mid to late May.

Figure 1. Area of the Peiligang culture (7000–5000 BC) in China

There are literatures that specifically study why agriculture was adopted in Yellow River basin. The soil in the area of the Peligang culture is part of the Loess Plateau, which has been ideal for developing agriculture. He (1985) points out that the soil in middle and lower Yellow River has been suitable for crop cultivation due to its dust granular form. The soil was moved by the air flow from the northwest inland of Asia, gradually spread and deposited in this area, being very loose. The loose structure made it easy for Neolithic people to farm using their clumsy wooden plows and shovels.

There has been extensive research into the transition from hunting and gathering to agriculture and settlement in China, leading some scholars to believe that although animal domestication also originated in the phase of hunting-gathering, the development of animal domestication is based on the development of plants domestication (Li and Lu, 1987). Li and Lu exclusively studied folk tales about farming, and found out how ancient people learned about cultivating seeds. The legends tell that ancient people found a tasty plant while gathering food, and tried to plant it. They experienced a lot of failures, and learned and more and more about cultivating crops during the process. Li and Lu believe that these ancient stories imply how people started farming crops. Yang (2006) suggests that the transition to agriculture can also be explained by population growth. He states that the Loess Plateau has been arid and dry, and the climate has been warm; plants for gathering and animals for hunting gradually reduced because of population growth, thereby forcing people to domesticate wild plants. The literatures above suggest that the combination of population growth and knowledge growth lead to the transition from hunter-gatherer to agricultural societies. With respect to modeling, there have been several modeling approach to study the origin of agriculture.

Zeder (2011) developed a model to study the origin of agriculture in the Near East, which is a verbal model that shows the timeline of the development of agriculture in Near East. Rindos et al. (1980) developed a verbal model for the origin and development of agriculture, which views agriculture as the outgrowth of evolutionary potentials that may develop whenever an animal consistently feeds upon any set of food plants. Bergin et al. (2015) developed an agent based model that explores the spread of agriculture using agent-based modeling, however, it does not study the origin of agriculture. There are other agent-based models that show the transition from one state to another. For example, Schelling's Model of Segregation (Schelling, 1971) shows how racial segregation emerges when every agent has a preference to live with same-race agents.

The existing models on the origin of agriculture are proved useful, but they fail to incorporate the interactions between human beings and the environment. The origin of agriculture is the result of the behaviors of many different people and their interactions with each other as well as the environment. For example, the interactions among different people, between people and plants, and between people and the land. They form a hierarchical system where people are the parts, and they make up the whole system – the communities of the Peiligang culture. People's individual decisions and behaviors will lead to the transition of the whole system. This is identical with the definition of complex system described by Simon (1996). In order to capture the transition of this system, I need to model such individuals, their decisions and interactions, and observe the emergence in the system. Therefore, a suitable approach to study the origin of agriculture is agent-based modeling. Nevertheless, here is no agent-based model that studies the origin of agriculture, or the transition from hunting and gathering to agricultural society.

In this paper, an agent-based model (ABM) is developed in Netlogo (Wilensky, 1999) to explore the transition from hunting and gathering to cultivation of wild plants in Peiligang culture. The study area is a square area where many villages Peiligang culture were concentrated. The elevation data of the area is used to inform land suitability for developing agriculture. A combination of the hypotheses in previous literatures regarding the origin of agriculture are used to inform agent behaviors.

3. Conceptual Model

This paper studies the origin of agriculture in the Peiligang culture using the "canonical theory of origins and development of social complexity" developed by Cioffi-Revilla (2005), and develops an agent-based model to simulate the transition from hunter-gather to agriculture society.

The canonical theory is used here to better understand the process of the Neolithic Revolution, the transition from hunting and gathering to agriculture and settlement, in societies of the Peiligang culture. The canonical theory provides a branching chart for the emergence of social complexity. The process of government emergence and political development is explained as resulting from a succession of non-deterministic phase transitions, based on path-dependent variations on the branching process. When societies face situational changes and recognize it, they can either take collective action or fail to do so, and when they do take collective actions, they can either succeed or fail. When collective actions of the society succeed, it accrues social complexity. The canonical theory of social complexity has been applied to study many social problems, including the social adaptation and long-term change in Inner Asia (Cioffi-Revilla et al., 2007), rise and fall of large polities in Zambezi Plateau (Bogle, 2014), simulation of the violent offending process (Dover, 2016), among other studies.

The case of Peiligang culture is analyzed using the canonical theory and the reviewed previous literatures. In Peiligang culture, people face the situational change that they do not have sufficient food resources from the nature as the population grows. In other words, they have reached the population capacity of the environment. Some of the people recognize the need for new sources of food, and those who have gained knowledge on plants while gathering plants will take actions and start farming millets. The situational change persists as the population continue to grow and natural food resources are being exhausted. Farmers can take further actions, pass their knowledge to other people, and train them to farm as well. If the actions succeed, they will transform into agriculture society and settle. As the number of non-cultivating people grows, there will be future situational changes and political development. Figure 2 is a brunching chart of the canonical theory applied to transition from hunter-gatherer to agriculture societies in the Peiligang culture. The canonical theory describes the process of my model. It could also be used to validate the model when it produces consistent outcomes; the model is designed in the way that results are not built in, as will be discussed in more details in Appendix A: Overview, Design concepts, and Details (ODD).

Figure 2. The transition from hunter-gatherer to agricultural societies in the Peiligang culture

Figure 3 shows the graphical user interface (GUI) of the model. It includes inputs to adjust parameters on the left, the display in the middle, and output charts tracking key variables over time on the right.

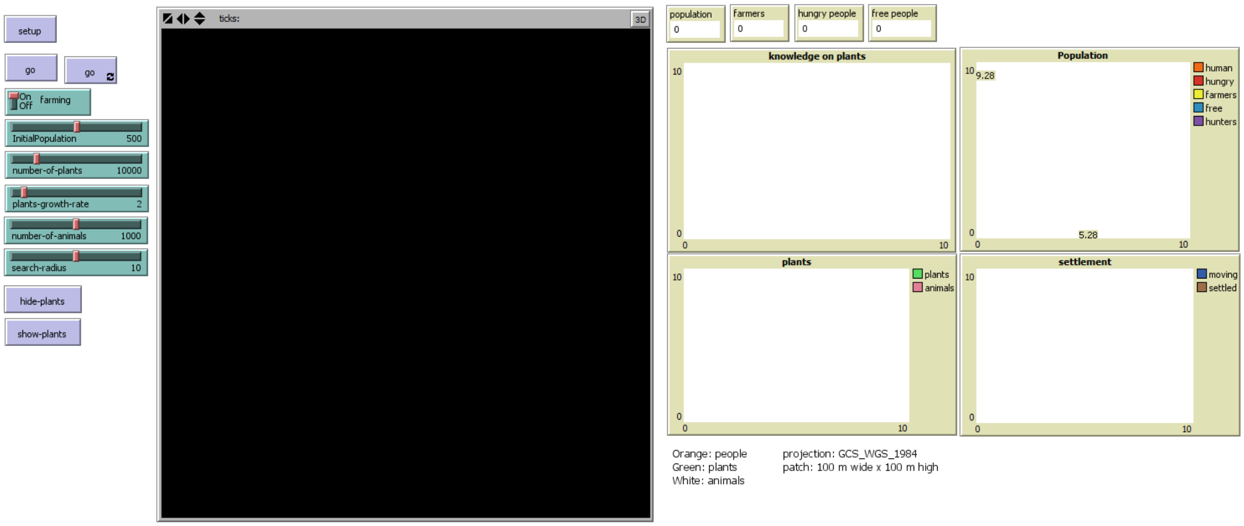

Figure 3. The model's graphical user interface

4. Results

Verification is the process of checking that the implemented model matches its design (North and Macal, 2007). For verification purpose, I have conducted code walkthroughs and parameter testing to ensure the model is working as designed, and there is no programming error in the code. The model was run on default setting as shown in Table 3 for 100 times, and the results presented are the average values of the 100 runs. The simulations were paused at a few points when significant changes in the system were observed. The simulation results at those points are analyzed in different charts, because some small but important changes of the numbers are hard to capture in the whole picture. In the charts, the blue line represents the total population, the red line represents hungry people, the grey line represents farmers, the yellow line represents hunter and gathers, and the dark blue line represents the non-cultivating people.

Around 20 years after the simulation started, I observe a situational change that has accrued, as shown in Figure 4. There are hungry people and the population is decreasing; as the same time, the amount of plants is dropping quickly. These numbers imply that population has reached environmental capacity and there is insufficient food from the nature. The average knowledge on plants is increasing as people gather plants. It is also observed that some people have become farmers. This suggests that some people have recognized the need for collective actions in response to the situational change. However, the number of hunter-gathers are still much higher than farmers, so the transition has not happened at this point yet.

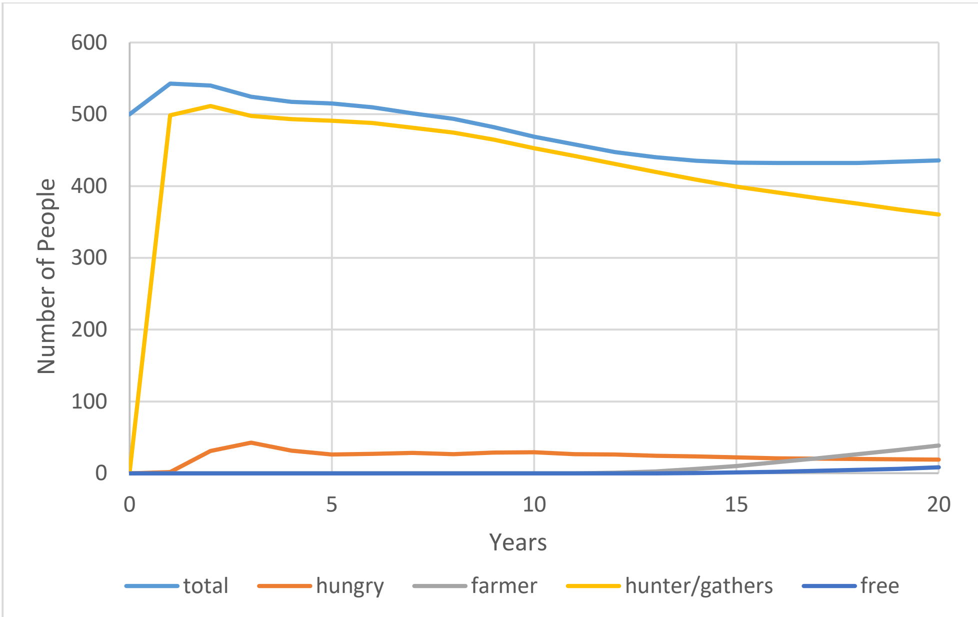

Figure 4. Results at 20 years (average values from 100 runs)

At around 30 years, I observe a rapid increase in the population, which is accompanied by the rapid increase of the number of farmers in the study area of Peiligang culture and decease of the number of hunter-gathers. This implies that the society is taking collective actions to develop agriculture. Farmers interact with others in the way that they can feed other people and pass their knowledge on plants to them, which allows more people to join farming. While hunting-gathering still dominates, the situational change persists.

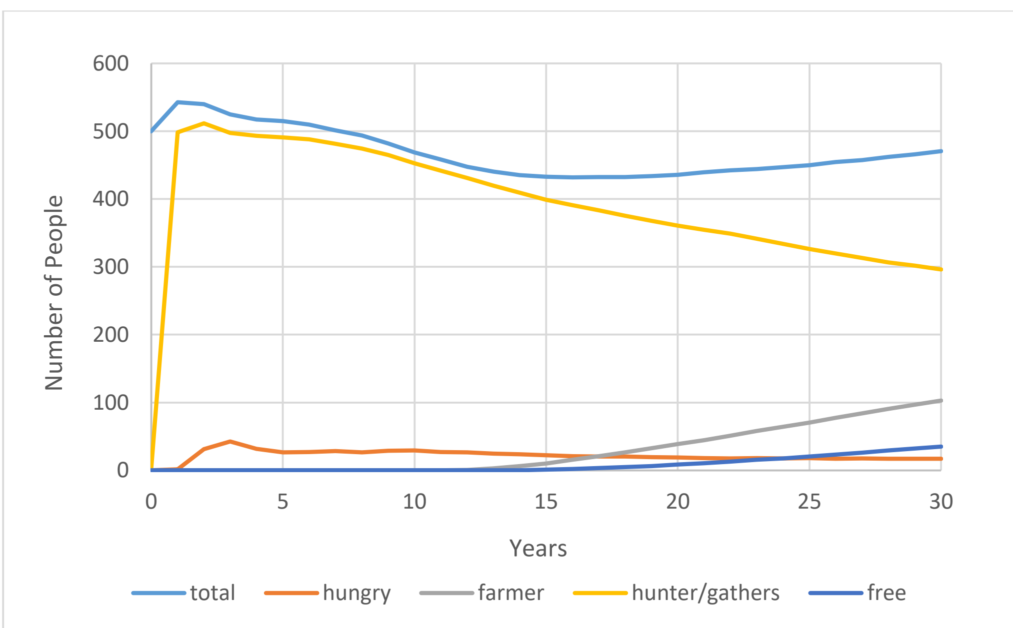

Figure 5. Results at 30 years (average values from 100 runs)

At around 50 years, the number of farmer continues to grow, and now it is about the same as the number of hunter-gathers. Although the number of plants keep decreasing, the number of hungry people keeps low, and population is growing. This phenomenon is consistent with the theory that hunting-gathering and farming have coexisted in the same phase. Also, I am able to observe that many people start to settle, and there are some non-cultivating people in the societies.

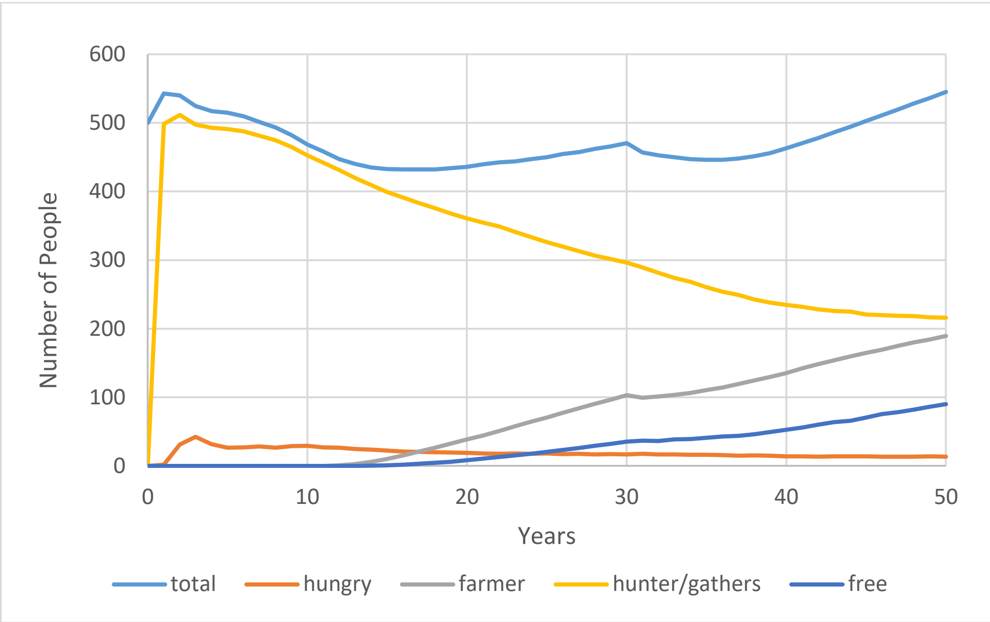

Figure 6. Results at 50 years (average values from 100 runs)

At about 100 years, the population has grown up to more than 2000, the number of farmers has surpassed the number of hunter-gathers, though many of the latter still exist. The number of settled people is far beyond the number of moving people. The number of plants has become considerably stable, since people no longer depend on wild plants for food. The number of hungry people is also kept very low, for about 30 to 40 hungry people out of a 2000 population. The collective actions in developing agriculture has succeeded, and the societies are transforming into an agricultural life-style. People are settled to farm their land year after year, and there is a large number of non-cultivating people who are available to work on other things that are significant for civilization.

Figure 10 shows a representative of the display at 100 years. It can be observed that there are many clusters spread on the map, which represents ancient villages. It is very likely that the collective effort needed in agricultural society, for example, sharing experience in farming and feeding other non-cultivating specialists, lead to the clustering.

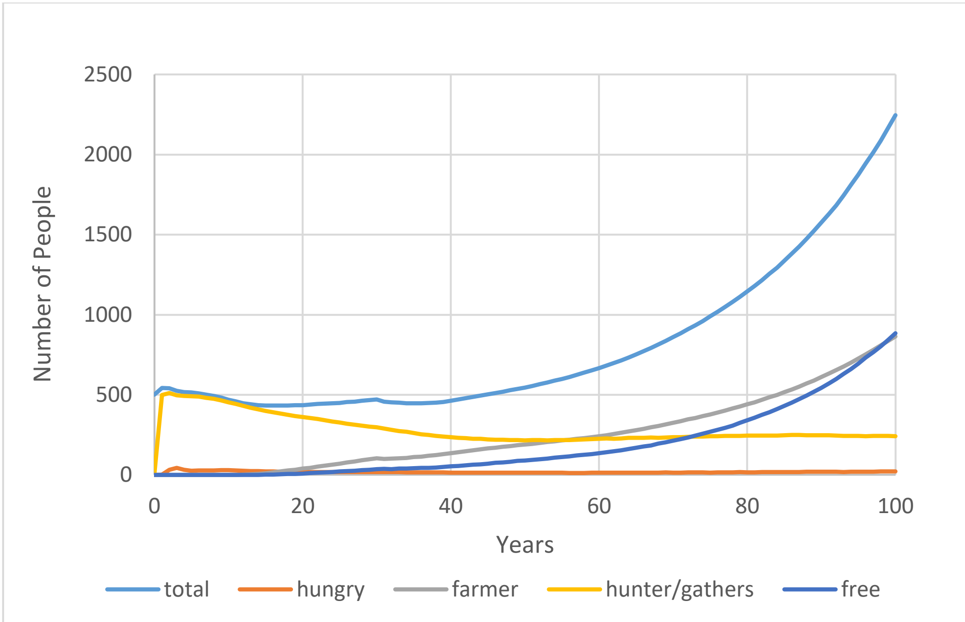

Figure 7. Results at 100 years (average values from 100 runs)

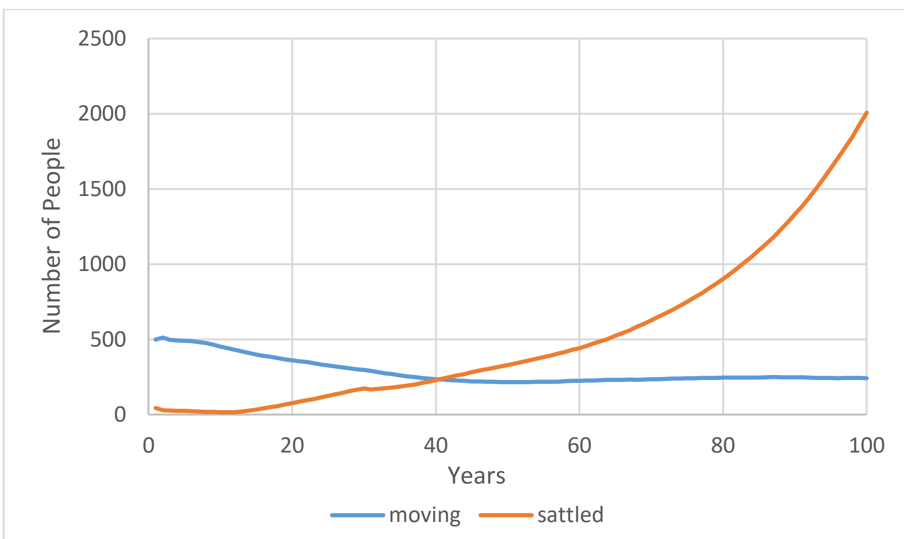

Figure 8. Settlement of human beings over 100 years (average values from 100 runs)

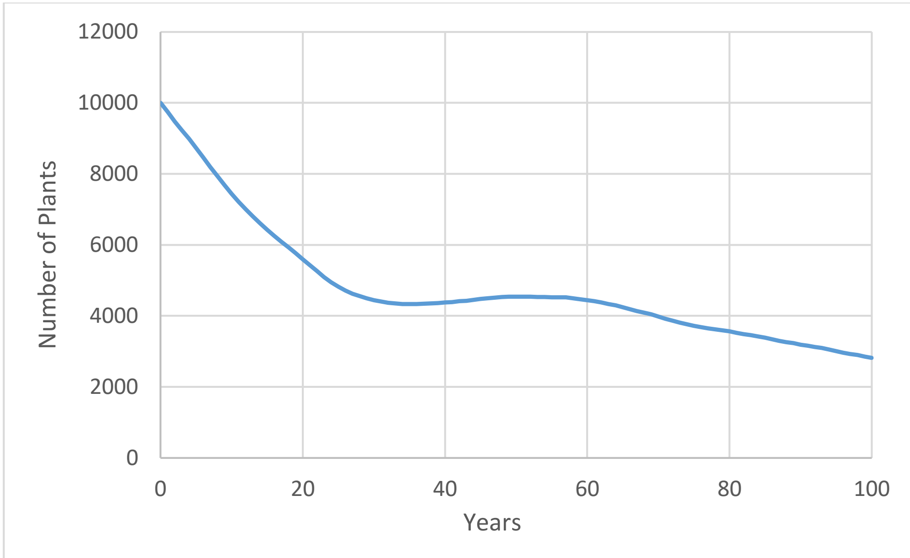

Figure 9. The amount of plants over 100 years (average values from 100 runs)

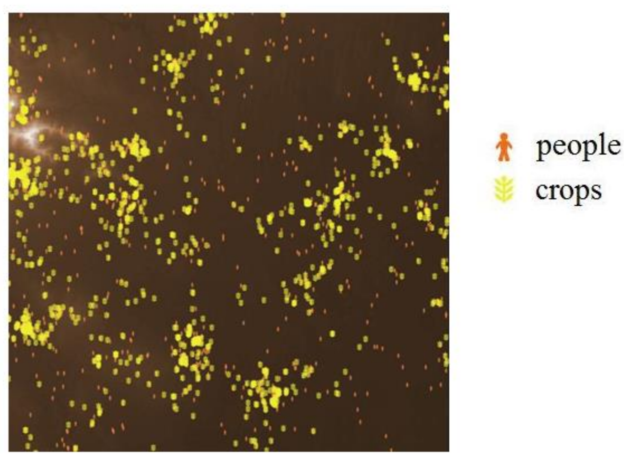

Figure 10. Display at 100 years. Wild plants are hidden. Yellow dots represent farming areas. Orange dots represent people that are not farmers.

I performed sensitivity analysis by changing the parameters. I analyzed three scenarios as following. Each setting was run for 100 times to generate the results.

Scenario 1: wild plants growth rate is increased to 5%, keeping all other parameters default. Now people have more sufficient food from the environment, and therefore, population did not significantly decrease. Agriculture still originated since the increasing population creates pressure on food supply, but the development of agriculture is obviously slower than default scenario.

Scenario 2: the number of wild plants is increased to 20000, keeping all other parameters default. The result is very similar to Scenario 1, except that the number of wild plants decreases much faster in this case. Agriculture still originated, and it developed even faster than the default scenario, because the population has grown larger due to ample food at the start, and agriculture is urgent to support such a big population.

Scenario 3: search radius decreased to 500 m, keeping all other parameters default. The population decreases at the start, since people have difficulty finding food from the nature. However, as people gained enough knowledge on plants and start farming crops, the population increases again. An interesting fact is that the clusters formed in this scenario are much smaller than those in the previous scenarios. The reason may be that a smaller search radius make people stay closer to each other.

Table 4 shows the settings and results of the three scenarios.

Parameter	Scenario 1	Scenario 2	Scenario 3
Results	The development of agriculture is slower than default scenario	The development of agriculture is faster than default scenario	Smaller clusters of human societies

Table 4. Settings and results of the three scenarios for sensitivity analysis

5. Summary

The model can be validated by comparing its results to the anthropological theories and findings in Section 2. The simulation results are also consistent with the canonical theory, matching the key phases in the branching process. The results are not designed, since the dynamic of the model is governed by two simple rules: population growth and gaining knowledge. The interaction among agents as well as interaction between agents and the environment contributed to the system level phenomenon, the transition from hunting-gathering to agricultural society.

The model has shortcomings, since it is based on many assumptions and estimations. I neglected the domestication of animals in this model, though animal domestication is also a big part of agriculture development. The reason is that I believe the rules of domesticating animals is very similar to domesticating crops in terms of modeling: getting the knowledge and getting hungry, so there is no point to simulate them both. My model could be improved by using empirical data to inform the parameters used in the model, though accurate data for Peiligang culture is hard to obtain. In the future, I also wish to add more geographical elements to the model. For example, how would the distance to water affect crop farming? However, the geological structures of the area of Peiligang culture from 8000 years ago is also hard to obtain.

This paper explores the origin of agriculture in Peiligang culture, uses the canonical theory as a framework to understand the transition process, and develops an agent-based model to simulate the transition using two simple rules: population growth and gaining knowledge on plants. Results show that, based on the two simple rules and assumptions, the model is able to generate results similar to the findings in previous literatures, and the model process could be explained by the canonical theory. Although the puzzle of the origin of agriculture remains controversial, the model presented in this paper provides a new approach to study this problem. Furthermore, since the usage of agent-based modeling in anthropology and archeology at this moment, the model may provide insights on how to approach those problems using agent-based modeling.

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Appendix A

Overview, Design concepts, and Details (ODD) of The Model of the Origins of Agriculture in Peiligang Culture

1. Overview

In the following section, a description of the model is given based on the Overview, Design concepts, and Details (ODD) protocol by Grimm et al. (2006). The OOD is a standard protocol for describing individual-based and agent-based models. I use it here to describe the elements of the model in details.

1.1 Purpose

The purpose of the model is to simulate the origins of agriculture in the Peiligang culture using existing theories on the origins of agriculture as discussed in Section 2. The intent of the model is to generate some of the significant phenomenon as in anthropological and archaeological studies, for example, the settlement of human beings. The model will help us better understand the transition from hunting and gathering to agricultural society happened thousands of years ago. It shows how the combination of origin theories may contribute to the transition, as well as the consequences of the transition.

1.2 Entities, State Variables and Scales

The model contains the following entities, from highest to lowest hierarchical scale: (1) Environment, (2) Parcels, and (3) Person (individual), which will be discussed in the following sections. The modeling world is a square area containing many ruins of the Peiligang culture. This is further divided into equal size Parcels, where the agents reside. The agents' (or Person) behavior is determined using behavioral rules designed according to the origin theories, which will be discussed in more details in section 3.3.3. Depending on their hunger status, knowledge on plants, and food availability around them, people will choose to hunt, gather, or start farming. Once a person becomes farmer, he or she will be able to feed and train up to three people around them. I design that a farmer can feed up to three people because of the fact that agriculture is more efficient. Figure 3 displays a flow chart of the decision process of agents. The model proceeds in one-year time steps, since the spring millet has one crop per year. The model is run for 100 simulation years to capture the transition from hunting-gathering society to agricultural society.

The modeling world is the area of Peiligang culture about 8000 years ago. Using DEM (Digital elevation model) data from SRTM (Shuttle Radar Topography Mission) data, this landscape encompasses a 25 square kilometers area in total, and the landscape was developed as a raster surface with each parcel size equal to 10,000 square meters, as shown in Figure 3. I do not have elevation data for the past landscape, therefore I am using recent data, and the landscape should not have changed too much over 8000 years. The simulation area is designed to include the cities of Zhengzhou and Xuchang, and the study area had a high concentration of villages in Peiligang culture. The extent of the study area is 33.991 ° N to 34.441 ° N horizontally, and 113.524 ° E to 114.069 ° E vertically. The parcel size of the original elevation data is 90 m, but it was resampled into 100 m. Each Parcel in this model is 100 m wide and 100 m high. The space is modeled explicitly and is based on the actual landscape of the study area. The elevation data is used to calculate slope and to determine if the land is suitable for developing agriculture. Table 1 lists all parcel parameters and provides a brief description of each.

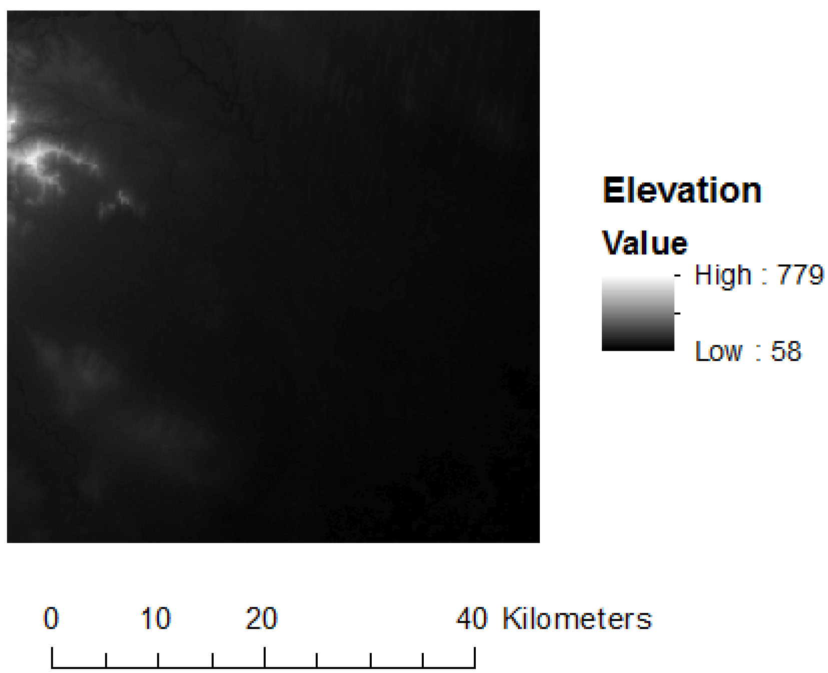

Figure 3. DEM of the study area in the Peiligang culture

Parameters	Description	Values
elevation	The elevation of the land here	0 to 799 m
degree	The slope degree of the land here	0 to 65 °

Table 1. Parameters of Parcels

At initialization, the agents (People) are added to the Parcels. The population data of people living in the study area is not available, and it is hard to estimate the population. Therefore, there is an input in the model that allows users to adjust how many people to create at start. People are created in groups, since hunter-gatherers are often grouped together based on kinship and band (or tribe) membership (Kiefer, 2002). Each group will contain 10 people that initially live near each other. One parcel can carry more than one person, but no more than 1000 people, which gives 10 square meters of area per person.

There are three types of agents in the model: people, plants, and animals. A person will become a farmer if he or she starts farming, and the plants being cultivated will become crops. People are characterized by unique attributes such as age, knowledge on plants, labor status, and hunger status. Table 2 lists all agent parameters and provides a brief description of each.

Parameters	Description	Values
age	The person's age	Larger than 0
sex	The person’s sex, either male or female	0 or 1
hunger-status	A binary variable that shows if the person is hungry or not	0 or 1
knowledge-on-plants	The person's knowledge on plants, which increases as he gathers plants for food	Larger than 0
free	A binary variable that shows if the person is free from producing food	0 or 1

Table 2. Parameters of People

1.3 Process Overview

The model proceeds in one-year increments. This time step was selected since spring millet, which was found to be cultivated by people in the Peiligang culture (Li, 1984), often has one crop per year. One year is also approximately the gestation period for a woman. Further, the yearly time step is suitable to simulate the transition from hunting and gathering to agriculture that took many years. More details will be discussed in the sections below. The model’s initialization process is discussed in Section 3.3.1; the agents’ behavior, which is determined via the Intensity Analyzer, is discussed in Section 3.3.3; and the model’s outputs are reviewed in Section 4.

2. Design Concepts

2.1 Individual Sensing, Interactions, and Decision-making

Agents are able to sense food availability (both animal agents and plants agents) near them, based on which they move around to search for food. People are also aware of other people near them, so that they can train other people with their knowledge on plants, or feed others if they have ample food. People are aware of the elevation and slope of the landscape, so they will only cultivate plants on suitable lands.

People in the model interact with each other in both direct and indirect ways. Direct interactions happen when a farmer teach or feed other people. Further, female people can give birth to new people if they are not hungry. People also have indirect interactions because of limited food availability and distribution. For example, if a person takes the food in one parcel, others will not be able to get food here, so they have to move or they may die because of hunger. People have interactions with animal and plant agents when people consume animal and plant agents for food. More details are explained in Section 3.3.3.

People are heterogeneous in terms of their age, sex, knowledge level on plants, hunger status, and labor status (hunter-gatherer, farmer, or free to do something else).

Stochasticity is seen in several processes. These include the agents' age and knowledge on plants at the initialization; agents' random movement searching for food; agent's likelihood to give birth to a new person when she is not hungry; agent's likelihood to die when it is hungry.

Decision-making processes are modeled at the agent level. Agents make decisions about where to look for food, what kind of food to get, and whether to cultivate plants or not. Decisions are based on factors such as food availability, the agents' knowledge, and some randomness. The agents' decision-making process is discussed in detail in Section 3.3.

2.2 Observation

I monitor the following statistics: the number of people, the number of resources, the number of people that are farmers, the number of hungry people, and number of free people. Statistics are collected by time step so that changes in behavior or trends can be easily assessed. The display also shows the movement and distribution of people, and it is monitored if people have settled. This is discussed further in Section 4. With respect to emergence, the outbreak, intensity, and spatial characteristics of the transition and settlement is an emergent phenomenon.

3. Details

The model was developed in Netlogo, a multi-agent programmable modeling environment (Wilensky, 1999), using the GIS extension.

3.1 Initialization

In this model, the environment is created as a 500 x 500 grid map, with each cell representing a 100 m by 100 m area. The DEM data is used to display the elevation of the study area. Agents are created according to the input parameter "population" and placed on Parcels randomly. Agents are heterogeneous and their age and knowledge on plants are distributed at initialization based on uniform random distribution. Plants and animal agents are created based on user specified parameters and randomly distributed on the map. All the default values and the parameters are summarized in Table 3.

3.2 Input data

Data used to create the geographic landscape came from the Global Aridity and PET Database (Jarvis et al., 2008), which provided the DEM data of my study area. The data is loaded into the model at initialization. Some parameters used in the model are based on author's estimation, and other parameters are user specified. Table 3 shows the default values of the parameters.

Parameter	Default values	Explanations
Global variables		
number of plants	1000 0	There will be 10000 units of plants on the landscape.
plant growth rate	2%	Up to 2% of the plants regrow each year.
number of animals	1000	There will be 1000 units of animals on the landscape.
Initial population	500	500 people will be created at the start.
People's variables		
age	random uniform [1, 30]	Assume that the age distribution follows a random uniform distribution from 1 to 30.
knowledge-on-plants	random uniform [1, 5]	People have some knowledge about plants at the start.
searching radius	1 km	The distance within which people can search for food.
probability of pregnancy	30%	The probability that a woman who meets the conditions for pregnancy will get pregnant during a year.
Parcels' variables		
elevation	0 to 799 m	The elevation of the ground.
degree	0 to 63.55 degrees	The slope of the ground.

Table 3. Default Values of Parameters

3.3 Submodels

A submodel is the decision model of People. Theories suggest that human beings started farming due to population pressure that exceeded the carrying capacity of the local environment (Sauer,1952; Lewis, 1968) as well as increased knowledge on plants. Although there are many different origin theories, all of them agree that fully charged ecological interaction provided the full knowledge of plants (Loewe at el., 1999). The model is designed to capture these theories, however, data are not available to inform all the parameters. Therefore, some parameters are selected based on common knowledge and my estimation.

People are designed to hunt and gather at first, and gain knowledge on plants when they gather plants. People will search for the closest plant or animal within their search radius, and capture it for food. As the number of people increases, some people can no longer find sufficient food. Given that they have enough knowledge to cultivate plants, they will try to do so and become a farmer. Therefore, there are two conditions for a person to become farmer: firstly, he or she can not find sufficient food; secondly, he or she has gained sufficient knowledge to cultivate plants. People can only farm on a land that has a slope smaller than 15 degrees, since irrigation on sloping ground will lead to soil and water loss. After someone became a farmer, he or she is able to feed up to three people, since the efficiency of farming is believed to be higher than hunting-gathering. This will free more people from producing food and to do many other things that is significant for civilization. At the end of each period, people who are hungry will die, and the female people who are not hungry and older than 12 years old may produce a child at a 30% chance. 30% is selected here so that on average one woman will have a child in three years. Also, people die when they are older than 30 years old.

Figure 4 shows the decision process of a person during one period (one year).

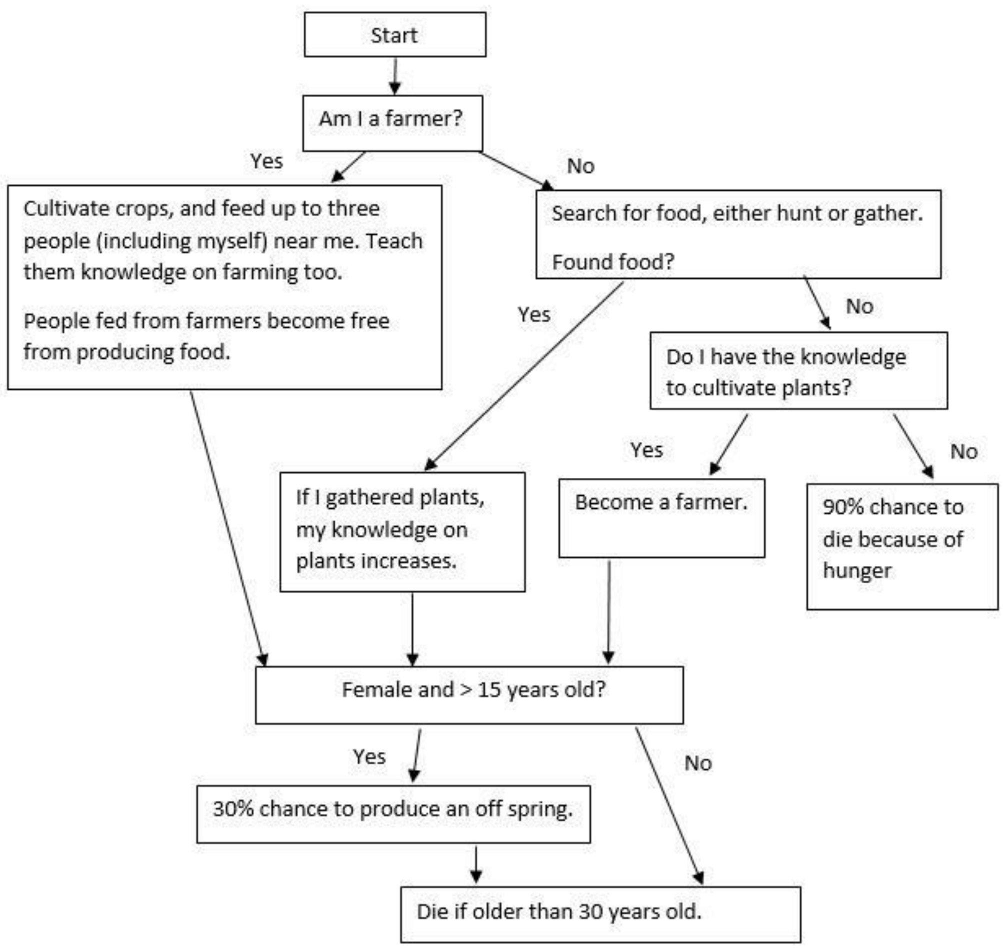

Figure 4. Decision Process of People

4. Model Output

The model exports a set of comparative statistics. These include the number of people, farmers, animals, and plants. In addition, the display shows where the agents are spatially located, and it is easy to observe that people are moving around at first, and later on they have settled in some places as agriculture develops.