Generating Anthropological and Archaeological Hypotheses in Okinawa through Agent-Based Simulation

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Abstract. This paper proposes an agent-based simulation (ABS) technique applied to generating anthropological and archaeological hypotheses. The basic idea is to develop a method to search for valid parameter sets of ABSs through intensive simulation experiments. In this case study, we focus upon the diffusion process of the agriculture and pottery in the Gusuku period (11th–14th centuries) in Okinawa, Japan. Following our intensive simulation results, we propose plausible but falsifiable hypotheses: 1) agriculture spread rapidly among native people and was, in the early stages, performed mainly by native people; and 2) the immigrant-style pottery was mostly used by immigrants and was not widely diffused among native people. These hypotheses should be verified by the new discovery of anthropological and archaeological evidence. Therefore, these ABSs will contribute to the literature in the fields of anthropology and archaeology in Japan.

Keywords: anthropology, archaeology, hypothesis generation

1 Introduction

Anthropology and archaeology are disciplines where human history is reconstructed by research into materials such as animal and plant residues, and the remains of human bones, artifacts (e.g., stone tools and pottery), and architecture. Recently, many excavations have been performed and much anthropological and archaeological evidence has been accumulated. Therefore, several cross-sectional situations at times and places in the past have been revealed by research into anthropological and archaeological evidence. However, if any changes occurred between cross-sectional situations, researchers need to generate hypotheses for these changes.

To generate hypotheses in conventional anthropology and archaeology, researchers have used the few materials at hand. Subsequently, they verify their hypotheses by investigating other evidence. However, missing materials and researchers' limitations can make it difficult to generate hypotheses. Even when hypotheses can be generated, these are often simple and of a limited number.

We are developing novel techniques to systematically generate plausible and falsifiable hypotheses through agent-based simulations (ABSs). So far, we have applied these techniques to ancient Japanese history; in particular, the native Jomon people played a formative role in the establishment of agrarian culture on the Japanese mainland [1,2]. In this paper, we will apply the same method to another Japanese case. Because ABSs explain emergent phenomena using a generative approach [3], they enable us to generate more numerous and complex assumptions than those generated by conventional methods. Additionally, these hypotheses enable us to narrow the ways of interpreting other currently undiscovered evidence.

In our previous papers [1,2], we discussed the problem of population dynamics after the introduction of agriculture on the Japanese mainland. The hypotheses were generated by ABSs. In the Japanese anthropological and archaeological problem of whether the native Jomon people or Chinese–Korean immigrants played a formative role in the establishment of agrarian culture during the Yayoi period (300 BC–250 AD), which has long been a source of controversy [4], we generated a new hypothesis that native Jomon people played a formative role in the establishment of agrarian culture by ABSs.

For most anthropological and archaeological studies in Japan, the required data, especially paleo-environmental records, are not widely available However, even if there are less data available, ABSs are able to compensate for this paucity of data. Referring to the conclusions of our previous papers, we will execute the same arguments in a different context in Japanese history.

In this paper, we deal with the case of the contact between hunter-gatherers and agrarian cultures in the Okinawa Islands of the southern Japanese archipelago. It is thought that agriculture was introduced to the Okinawa Islands from the 9th to the 10th century, before the start of the Gusuku period in the 11th century [5]. This hypothesis is supported by the discovery of grains excavated from 9th century ruins. The sudden onset of agriculture is assumed to be because of the immigration of agricultural peoples.

There were large differences before and after the start of the Gusuku period. First, there was a population explosion: there are seven-times more ruins in the Gusuku period than in the Shell midden period, an antecedent of the Gusuku period [6]. It is thought that the population increased during the Gusuku period because of the start of agriculture. Second, there were large differences in anthropological morphology. The bones of the people before the Gusuku period indicate that they had low and small faces [7-9], while the bones of the people in the Gusuku period show that they were heavyset and tall, with dolichocephaly(long narrow head) It is assumed that this change also follows the population replacement by the immigrants bringing agriculture from the Japanese mainland. Third, in evidence of immigrants bringing agriculture from the Japanese mainland, there is a study of ancient mitochondrial DNA (mtDNA) from the people of the Gusuku period [10]. The mtDNA haplogroup D4, which has high frequency on the Japanese mainland, also has high frequency in the people of the Gusuku period. Fourth, there were large differences in the style of pottery. In the Gusuku period, while the pottery of the distribution products—which is influenced by the pottery style of the Japanese mainland—was widely propagated, the style of pottery made in the settlement varied from the conventional native style to a different style, which is an imitation of the distribution products [11].

However, the process of these changes following the introduction of agriculture is unknown. Therefore, we apply ABSs to the hypothetical processes of the anthropological and archaeological change following the introduction of agriculture. Similar to our previous study [2], the ABSs in this paper deal with the diffusion process of the trait gene, mtDNA, and the vertical transmission of pottery styles under agricultural diffusion. In this study, we also add the horizontal transmission of pottery styles to the previous simulation model.

2 Description of the Simulation Model based on ODD Protocol

Our simulation model follows the Overview, Design concepts, and Details (ODD) protocol [12,13]. This protocol is intended to address the criticism that agent-based models lack reproducibility. Furthermore, it aims to improve the integrity and standardization of the model description.

2.1 Agent and State Variable

The agent in our model was defined as an ancient person with the following variables.

Identity (ID) Number and Spatial Placement. The following information was assigned to an agent: an ID number and a coordinate position [X: 50 cells, Y: 50 cells] within a two-dimensional space. This space represented the main island of Okinawa. Within our simulation model, the simulation space represented a very abstract space. This meant that the space was not directly related to real geographical space, because we mainly focused on discussing the relative diffusion of trait genes, mtDNA, and pottery style and agriculture. Considering the gene flow and pottery style relative to the speed of agricultural diffusion, the abstract space was sufficient for considering the issues at hand. The size of the space within our simulation was defined by the speed of diffusion of agriculture as described below.

Sex. The agent was male or female.

Life Expectancy and Age. Upon creation (birth), an agent was given an individual life expectancy based on the mortality table. If the age of the agent exceeded the life expectancy, the agent was removed (died). Supposing that the mortality table has not changed from ancient times up until the modern period, we created this by reflecting an infant mortality rate of 20% up to recent years on that of people of the Jomon period [14].

Food Production System. The food production system variables were hunting and gathering or agriculture. This system changed from hunting and gathering to agriculture through the diffusion of agriculture based on the assumption that the difficulty of food obtained by hunting and gathering in the late Shell midden period, an antecedent of the Gusuku period, introduced an opportunity for this conversion process [5]. However, we assumed that the opposite condition did not hold, because there is no evidence of the diffusion of hunting and gathering during this period.

Marriage Institution. The marriage institution variable for the male agent was monogamous or polygamous. To date, the type of marriage institutions that prevailed during the Shell midden period and the Gusuku period have not been ascertained. However, in the Yayoi period (300 BC–250 AD) of the Japanese mainland, it has been assumed that polygamous marriage occurred based on descriptions of this type of marriage contained in "*Gishi-Wazin-Den*," an ancient Chinese text on the Yayoi period customs. According to this text, some men of high status had four or five wives, and there were even some men of normal status who had two or three wives. Therefore, together with other references, it is assumed that polygamous marriage has been widely diffused in the Japanese mainland from the Yayoi period up until the early modern period. Additionally, we postulated that sustaining more than one wife—polygamous marriage—requires a surplus of food. Therefore, in our simulation model, if the male agent included both of the following variables: polygamous and a high-yielding food production system, namely agriculture, then the agent was assumed to be married to three female agents. A new agent (child) inherited the father agent's marriage institution.

Trait Genes. Trait genes determine trait characteristics. Originally, it was thought that trait characteristics are determined through the involvement of many genes in a complex manner. However, to simplify this for the simulation, it is assumed to be composed of a major pair of alleles: the native-type gene (N) and the immigrant-type gene (M). When a new agent (child) is created (born), the agent inherits either of the father agent's and either of the mother agent's alleles; i.e., the agent's combination of alleles is NN, MM, or NM. In accordance with these combinations, each agent is classified as one with native or immigrant traits. Specifically, a NN agent comprises traits of the native people, a MM agent comprises immigrant traits, and a NM agent displays mixed traits (mixed people) and comprises immigrant traits, because the individuals were determined to be immigrants based on the assumption that a person with even a small amount of immigrant traits is an immigrant.

MtDNA Haplogroup. The mtDNA haplogroup variable for an agent was haplogroup D4, haplogroup M7a, or other. The mtDNA, which is the cell organelle DNA of mitochondria, is inherited maternally and relatively easy to extract from human bone remains. Therefore, mtDNA analysis is a useful way of investigating the origin of the maternal line of ancient peoples. In the frequency of the mtDNA haplogroup of people of the Gusuku period, the frequency of M7a, considered as native type, was 28.6%. In contrast, the frequency of D4, with high frequency in the Japanese mainland, was 35.7% [9]. In our simulation model, when a new agent (child) was created (born), the agent inherited the mother agent's mtDNA haplogroup as described below.

Pottery Style. The pottery style variable was either the native style or the immigrant style. In our simulation model, for the sake of convenience, we restricted the pottery style to either the native or immigrant styles. The argument made by Tsude [15] that women produced pottery during the Yayoi period is supported by an extensive ethnographic literature [16]. Therefore, within the field of Japanese archaeology, it has generally been held that it was women who produced pottery during ancient times. Therefore, in our simulation model, the inheritance of pottery is assumed to be maternal. Additionally, because the pottery style had rapidly become varied, we must consider that the diffusion pattern of pottery styles contains not only the vertical transmission, but also the horizontal transmission. Therefore, as will be described later, we also simulate the horizontal transmission in addition to the vertical transmission. The horizontal transmission also shows reversibility; i.e., there are changes not only from the native style to the immigrant style, but also from the immigrant style to the native style.

2.2 Process Overview and Scheduling

Our simulation model proceeded according to annual time steps; the annual time step was a year. Each year, the four submodels of each agent were executed in turn as follows: diffusion of the agriculture rule, diffusion of the pottery style rule, marriage rule, and moving rule. Additionally, agents were processed in a random order during each year.

2.3 Design Concepts

Our simulation model corresponded to seven out of the 11 design concepts contained in the ODD protocol (Table 1). The model was simple, and we considered that the description of the model and design concepts were sufficient to indicate reproducibility.

Table 1. Design Concepts

Number	Design concepts	Elements
1	Basic Principles	Trait gene, mitochondrial DNA (mtDNA) haplogroup, and pottery style was diffused under the increased population based on the food production system by the diffusion of agriculture
		• For the diffusion of agriculture and pottery styles, we apply the SI model
		• For the increase of people, we apply Malthus' theory
		• For the inheritance of the trait gene, we apply Mendel's laws
2	Emergence	Diffusion of agricultural culture changes the total number of agents, the ratio of people with the immigrant traits, the ratio of the immigrant-style pottery, the frequency of mtDNA haplogroup D4, the composition ratio of each descendant of agriculture holders and the composition ratio of each descendant of immigrant-style pottery holders
3	Adaptation	• If an agent is near another agent with agricultural culture, it introduces an agricultural culture at a given rate
		• If an agent is near another agent with another style of pottery, it introduces another pottery style at a given rate
4	Sensing	• Recognizing whether an agent is near another agent with agriculture
		• Recognizing whether an agent is near another agent with the another pottery style
		• Recognizing whether a male agent is near the female agent
5	Stochasticity	• Life expectancy
		• Spatial placement at the start of the simulation
		• Allocation of mtDNA haplogroup at the start of the simulation
		• Introduction of agriculture
		• Introduction of pottery style
		• Selection of female agent for marriage
		• Sex of child agent
		• Combination of trait genes
		• Move in random direction
6	Collectives	The number of agents created is determined by the number of hunter–gatherer or agricultural agents
7	Observation	• Total number of agents
		• Ratio of people with immigrant traits
		• Frequency of mtDNA haplogroup D4
		• Ratio of the immigrant-style pottery
		• Composition ratio of each descendant of agricultural culture holders
		• Composition ratio of each descendant of the immigrant-style pottery holders

2.4 Submodels

Diffusion of the Agriculture Rule. The diffusion of agriculture occurred through neighboring agents and inheritance from a father agent. In our simulation model, we assumed that these very simple patterns of cultural transmission followed the conventional susceptible–infectious (SI) model of infectious diseases.

In the diffusion from a neighboring agent, if the agent's food production system was hunting and gathering, while that of all the other neighboring agents was agriculture within a given cell radius (the extent of diffusion occurring within a cell range was: one cell [narrow], three cells [moderate], and five cells [wide]), the agent's food production system would then be transformed into agriculture. This transformation was based on a given probability (introduction rate: difficult [0.1%], middle [0.5%], and easy [1.0%]). Conversely, in the inheritance from a father agent, and according to the marriage rule described below, when a new agent (child) was created (born), the agent inherited the food production system from their father agent.

Diffusion of the Pottery Style. The diffusion of pottery style occurred through the vertical transmission from a mother agent and the horizontal transmission from a neighboring agent. In the vertical transmission, as mentioned above, the argument made by Tsude [15] that women produced pottery during the Yayoi period is supported by an extensive ethnographic literature [16]. Therefore, within the field of Japanese archaeology, it has generally been held that women produced pottery during ancient times. Therefore, in our simulation model, the vertical transmission is the inheritance from a mother agent. In the horizontal transmission, this is reversible; i.e., there are changes not only from the native style to the immigrant style, but also from the immigrant style to the native style. Specifically, the agent's pottery style would change to another pottery style used by a different agent within a given cell radius (the extent of diffusion occurring within a cell range was: one cell [narrow], three cells [moderate], and five cells [wide]). This transformation was also based on a given probability (introduction rate: impossible [0%], difficult [0.1%], middle [0.5%], and easy [1.0%]).

In summary, we simulate two pottery-style diffusion patterns: 1) maternal vertical transmission pattern, and 2) vertical and horizontal transmission pattern.

Marriage Rule. A new agent (child) was created (born) as a result of the marriage of a male and a female agent. The male agent was married to a female agent selected randomly from all of the female agents within three surrounding cells. Furthermore, a new agent was created according to the population growth rate of the mother agent's food production system and at the same spatial placement as that of the mother agent. The sex of the new agent was allocated according to a 50% probability of being male, along with a life expectancy and age of 0. For the trait gene, as previously explained, the new agent inherited either of the father agent's alleles and either of the mother agent's alleles. Additionally, the new agent inherited the food production system and the marriage institution from their father agent, and the pottery style and mtDNA haplogroup from their mother agent. Moreover, as mentioned above, the male agent could be simultaneously married to three female agents only when associated with both the polygamous and agriculture variables.

Moving Rule. Within each step, an agent moved one cell in random directions within the simulated space.

2.5 Initialization

Time Span of the Simulation. The time span of our simulation was 400 years (400 steps), extending from the beginning era to the final era of Gusuku period.

Population Growth Rate Based on the Food Production System. The population growth rate of agriculturalists was higher than that of hunters and gatherers. As mentioned above, there are seven-times more ruins in the Gusuku period than in the Shell midden period, an antecedent of the Gusuku period [5]; i.e., it is thought that the population also increased in the Gusuku period at the same rate of increase. Considering these evidences, working backward from a sevenfold increase in the population over 400 years, we assumed that the increase in the agricultural population was 0.6% per year. Conversely, considering that the growth rate of the agriculturalist population had not increased during the Shell midden period, we assumed that the growth rate of the hunter–gatherer population was 0.0% per year.

Speed of the Diffusion of Agriculture. The speed of diffusion of agriculture in our simulation model comprised the range of cells associated with the diffusion and introduction rate. The range of diffusion cells corresponded to the distance within which cultural exchange would occur while they were in contact with each other. As mentioned above, we assumed there were three possible degrees: narrow (one cell), moderate (three cells), and wide (five cells). The introduction rate corresponded to the difficulty associated with the introduction of agriculture. Here, we assumed three degrees: difficult (0.1%), medium (0.5%), and easy (1%). The level of difficulty did not relate to agricultural techniques, but rather to the adequacy of the environment and culture required for the acceptance of the new agricultural practice. These values were set assuming that even when the range of cells was narrow and the introduction rate was difficult, approximately 400 years were required for the majority of agents to have agriculture.

Pattern of the Diffusion of Pottery Styles. To show the pattern of the diffusion of pottery styles, as mentioned above, we simulated two patterns as follows in each simulation case

- First pattern (vertical transmission): The pottery style is only inherited from a mother agent.
- Second pattern (vertical and horizontal reversible transmission): The diffusion of pottery styles occurred through neighboring agents and inheritance from a mother agent. Additionally, in the horizontal transmission, this is reversible; i.e., there are changes not only from the native style to the immigrant style, but also from the immigrant style to the native style.

Speed of the Diffusion of Pottery Styles. Like the speed of agriculture, the speed of diffusion of pottery styles in our simulation model comprised the range of cells associated with the diffusion and introduction rates. The range of diffusion cells corresponded to the distance within which pottery style exchange would occur while agents were in contact with each other. We assumed there were three possible degrees: narrow (one cell), moderate (three cells), and wide (five cells). The introduction rate corresponded to the difficulty associated with the introduction of a pottery style. Here, we assumed four degrees: impossible (0%), difficult (0.1%), medium (0.5%), and easy (1%).

State Variables of the Initial Native People and Immigrants. The simulation run commenced with the initial native people and immigrants whose state variables are described below.

Initial native people.

- Number of agents: 1800
- Sex ratio: male and female 50% each
- Trait gene: NN
- Spatial placement: uniformly and randomly placed
- Food production system: hunting and gathering
- Marriage institution: monogamous
- Pottery style: native style
- MtDNA macrohaplogroup: In total, 0.0% had haplogroup D4, 47% had haplogroup M7a, and 53% had another haplogroup. With reference to [10], [17,18], we calculated the frequencies except for the haplogroup D4, which was derived from the Japanese mainland.

Initial immigrants

- Number of agents: 200
- Sex ratio: male and female 50% each
- Trait gene: MM
- Spatial placement: placed in the center of the upper side of the simulated space [X: 25, Y: 50]
- Food production system: agriculture
- Marriage institution: monogamous or polygamous in each simulation case
- Pottery style: immigrant style
- MtDNA macrohaplogroup: With reference to Sakahira [19], the frequency of mtDNA of medieval people on the Japanese mainland, 53.0% had haplogroup D4, 7% had haplogroup M7a, and 40% had another haplogroup.

2.6 Number of Simulation Cases and the Evaluation Index

There were a total of 180 simulation cases—that is, cases combining each of the above parameters. In each simulation run, the number of agents might increase from 200 to 20,000. This means that each run takes very long comuttion time. Thus, although the numbers of runs are not enough, all cases were run only ten times. The random seed value of these ten runs was the same across cases. The improvement of computational efficiency will be one of our future issues.

The main evaluation index in our simulation results was the total number of agents, the ratio of people with immigrant traits, the frequency of mtDNA haplogroup D4, and the ratio of the immigrant-style pottery across all agents 400 years later.

For the total number of agents, we investigated how much the population increased among cases. For the ratio of people with immigrant traits, 80% was considered a measure of demographic transition. For the frequency of mtDNA haplogroup D4, with reference to Shinoda [10], the value of 35% is regarded as the results along the anthropological facts. For cases that met these requirements, we depicted a time series of the composition ratio of each descendant of the agriculture holders to investigate who had performed agriculture.

Additionally, to discuss the pottery-style diffusion patterns, among cases of only vertical transmission and cases of vertical and horizontal transmission, we investigated how much the ratio of immigrant-style pottery is high. Furthermore, in cases in which the ratio of immigrant-style pottery was more than about 80%, we investigate how to diffuse the immigrant-style pottery by depicting a time series of the composition ratio of each descendant of the immigrant-style pottery holders.

3 Results and Discussion

3.1 Difference in the Total Number of Agents Depending on the Speed of Agricultural Diffusion

The total number of agents varied depending on the speed of diffusion of agriculture. Cases in which the speed of agricultural diffusion is rapid (e.g., a wide [5 cells] range of diffusion cells and an easy introduction rate [1%]) had a larger total number of agents than cases in which the speed of agricultural diffusion is slow (e.g., a narrow [1 cell] range of diffusion cells and a difficult introduction rate [0.1%]) (Fig. 1). Considering these, we generated a hypothesis that the reason for population explosion in the Gusuku period is that agriculture had been diffused quickly and widely. The results coincide with our intuitions, however, the interpretations of the results should be further investigated, whether they are a possible simulation artifact or it is a natural outcome.

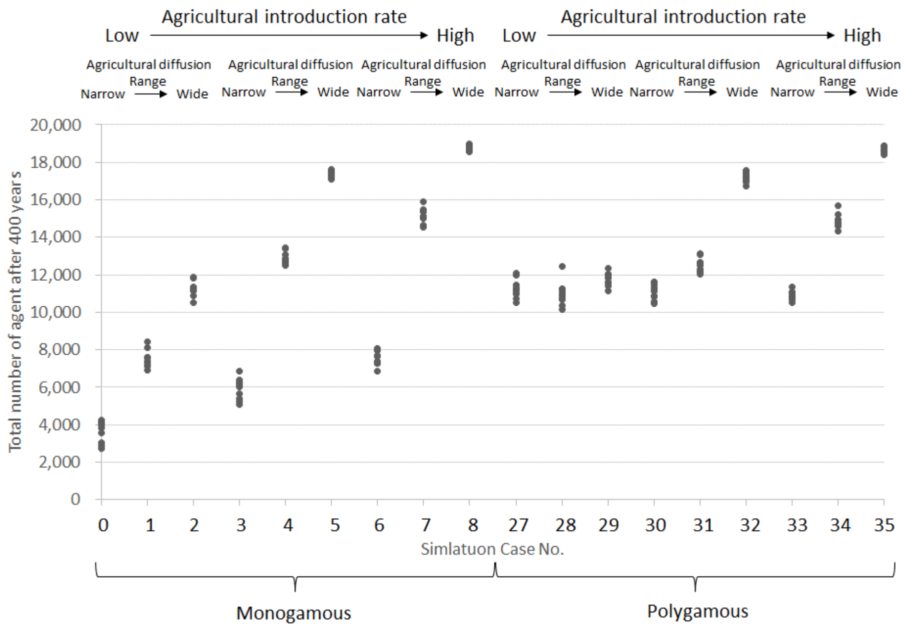

Fig. 1. Difference in the total number of agents depending on the speed of agricultural diffusion

3.2 Difference in the Ratio of People with Immigrant Traits and the Frequency of mtDNA Haplogroup D4 Depending on the Marriage Institution and the Speed of Agricultural Diffusion

Cases of Monogamous Marriage. In the ratio of people with immigrant traits and the frequency of mtDNA haplogroup D4 400 years later, all cases of monogamous marriage did not reach 80% of the ratio of people with immigrant traits, which is a measure of demographic transition and 35% of the frequency of mtDNA haplogroup D4 (Fig. 2). In general, cases in which the speed of the diffusion of agriculture was slow (e.g., a narrow [1 cell] range of diffusion cells and a difficult introduction rate [0.1%]) indicated a higher ratio of people with immigrant traits and a higher frequency of mtDNA haplogroup D4. Conversely, cases in which the speed of the diffusion of agriculture was rapid (e.g., a wide [5 cells] range of diffusion cells and an easy introduction rate [1%]) indicated a lower ratio of people with immigrant traits and a lower frequency of mtDNA haplogroup D4. Demographic transition did not occur because once agriculture had diffused among native people at an early stage, their population increased at a high rate of agricultural population growth.

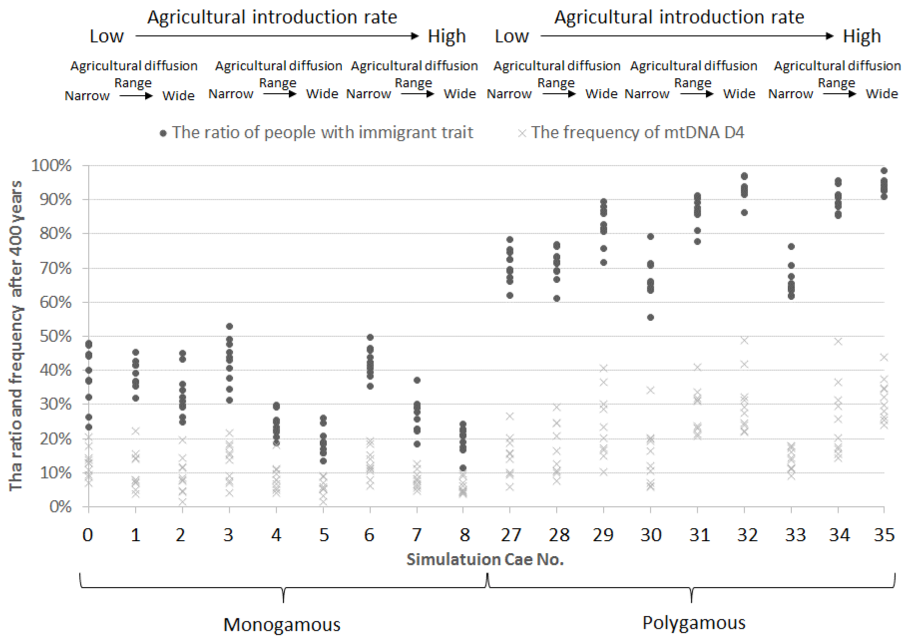

Fig. 2. Difference in the ratio of people with immigrant traits and the frequency of mtDNA haplogroup D4 depending on the marriage institution and the speed of agricultural diffusion

Cases of Polygamous Marriage. The ratio of people with immigrant traits and the frequency of mtDNA haplogroup D4 after 400 years varied depending on the speed of the diffusion of agriculture (Fig. 2). In cases of polygamous marriage, some cases of slow-speed diffusion of agriculture did not achieve a population of 80% with immigrant traits and 35% with mtDNA haplogroup D4 after 400 years. By contrast, some cases demonstrating a significant speed of agriculture diffusion demonstrated a population of 80%

with immigrant traits and 35% with mtDNA haplogroup D4 after 400 years. These results demonstrate that in cases in which polygamous marriage was combined with the diffusion of agriculture, demographic transition was facilitated by the wider diffusion of agriculture. This could be attributed to a time lag between the diffusion of agriculture and polygamous marriage, which influenced the increasing populations of native people and immigrants. Specifically, the density distribution of immigrants meant that the number of immigrants increased during the earliest stage. However, polygamous marriage and mtDNA haplogroup D4 remained within immigrants because these traits were inherited from parent agents. Consequently, the neighboring native people came to possess agriculture by diffusion. Furthermore, in a situation in which immigrant neighbors engaged in agriculture displayed a higher population growth rate, the immigrant trait gene type and mtDNA haplogroup D4 was diffused through polygamous marriage. That is, for wider diffusion of the immigrant trait gene type and mtDNA haplogroup D4 to occur, it was necessary for immigrant neighbors to demonstrate use of agriculture and a higher population growth rate. Although whether there is a polygamy marriage has been unknown in Gusuku period, our simulation results suggest the possibility of the existence of a marriage institute in which people with immigrant trait genes and mtDNA haplogroup D4 can be distributed preferentially.

To discuss the diffusion process of agriculture in the Gusuku period, we investigated who had performed agriculture. The composition ratio of descendants of those practicing agriculture showed a slight degree of mixing of native and immigrant descendants but that immigrant descendants constituted the majority at the early stage in cases that entailed slow diffusion of the agriculture (Simulation case number 29, Run 7) (Fig. 3). Both descendants thus came to account for most of those who engaged in agriculture as a result of marriage. These results suggest, as our first hypothesis, that agriculture was performed mainly by immigrants in the Gusuku period. In contrast, for cases demonstrating significant and rapid diffusion of agriculture, at the earliest stage, only the descendants of immigrants were the holders of agriculture. However, shortly thereafter, native descendants constituted the majority (Simulation case number 35, Run 9) (Fig. 4). Consequently, both descendant groups became the majority group through marriage. These results indicate that it is probable that even if agriculture was widely diffused among the native people, demographic transition could occur. These results suggest, as our second hypothesis, that agriculture was introduced to and performed mainly by native people in the Gusuku period. Both these hypotheses are probable. However, as described above, considering that the reason for population explosion in the Gusuku period is the rapid and wide diffusion of agriculture, the latter hypothesis that the speed of agricultural diffusion was rapid and agriculture was performed mainly by native people is more probable.

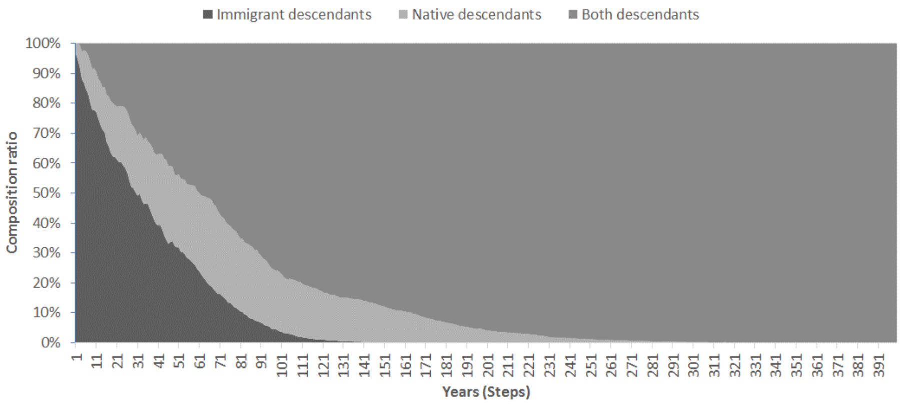

Fig. 3. Composition ratio of each descendant with agricultural holders in cases that the diffusion speed of agriculture was slow (Simulation case number 29, Run 7)

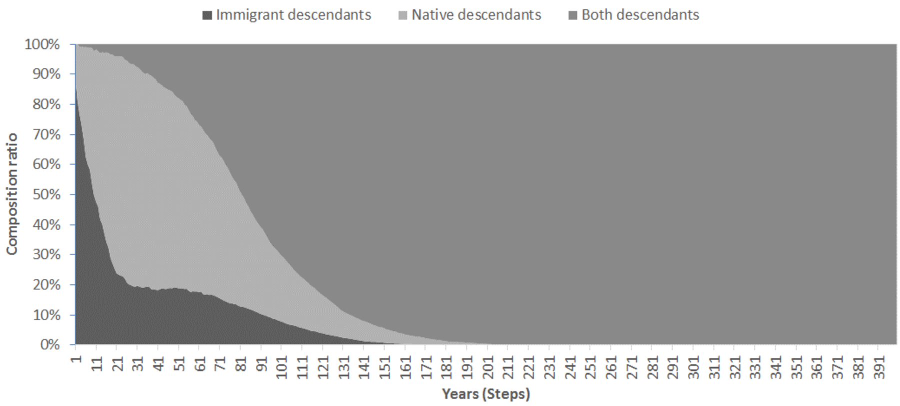

Fig. 4. Composition ratio of each descendant with agricultural holders in cases that the diffusion speed of agriculture was rapid (Simulation case number 35, Run 9)

In summary, our simulation generated new hypotheses about the processes of population explosion and agricultural diffusion. These are as follows: 1) agriculture was introduced by immigrants and diffused widely and quickly among native people; 2) rapid diffusion of agriculture among the native people created the population explosion in the Gusuku period; and 3) during the population explosion, demographic transition occurred by through the marriage institution (e.g., polygamous marriage) to distribute the immigrant trait gene and mtDNA haplogroup D4 preferentially.

3.3 Diffusion of Pottery Styles

Vertical Transmission of Pottery Styles. In cases of polygamous marriages, even in only the vertical transmission of pottery styles, the ratio of immigrant-style pottery in the cases of rapid diffusion of agriculture (e.g., a wide [5 cells] range of diffusion cells and an easy introduction rate [1%]) is higher than that in the cases of slow diffusion of agriculture (e.g., a narrow [1 cell] range of diffusion cells and a difficult introduction rate [0.1%]) (Fig. 5). The reason is assumed to be that after the female immigrant population increased by polygamous marriage within immigrants in the earliest period, during the population explosion by diffusion of agriculture among native people, the immigrant-style pottery was widely diffused though marriage with many female immigrants. These results support the hypothesis that the speed of agricultural diffusion was rapid and agriculture was performed mainly by native people. The process of pottery diffusion in this case is that immigrant-style pottery had been held mostly by immigrants and had not been diffused among native people because of vertical transmission without horizontal transmission.

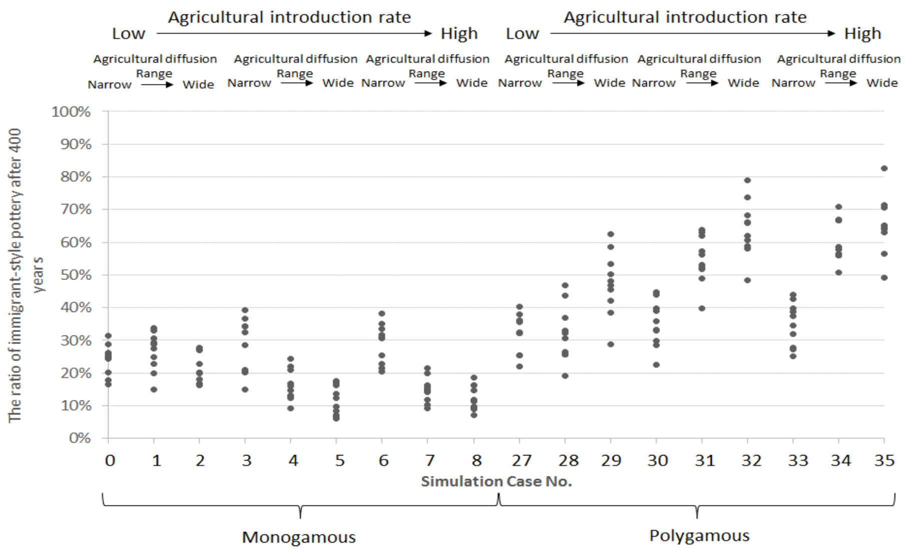

Fig. 5. Difference in the ratio of immigrant-style pottery depending on the speed of agricultural diffusion in the vertical transmission of pottery styles

Vertical and Horizontal Transmission of Pottery Styles. In the case of polygamous marriage and slow speed of diffusion of pottery styles, the high diffusion ratio of immigrant-style pottery holders was shown because the effect of vertical transmission of pottery style is stronger than that of horizontal transmission (Fig. 6, Simulation case number 194). The reason is the same as above. Moreover, the ratio of immigrant-style pottery after 400 years varied depending on the speed of the diffusion of agriculture. The ratio of immigrant-style pottery holders in the cases of rapid diffusion of agriculture is higher than that in the cases of slow diffusion of agriculture (Fig. 6).

However, in cases of the rapid diffusion of pottery styles, because of the reversibility of changes in pottery styles, there are some runs in which the immigrant-style pottery disappeared by stochasticity. That is, in cases of the rapid diffusion of agriculture and pottery styles, there are some runs in which the immigrant-style pottery was dominant and there are some runs in which the immigrant-style pottery disappeared. Investigating the process of pottery-style diffusion in these cases, there is only a slight difference between slow pottery diffusion (Fig. 7) and rapid pottery diffusion (Fig. 8) in the ratio of native descendants with immigrant-style pottery holders. That is, in both cases, within the immigrant-style pottery holder group, native descendants were small.

In summary, our simulation generated new hypotheses of the diffusion process of pottery styles. These are as follows: 1) the high ratio of immigrant-style pottery holders need polygamous marriage and rapid speed of agricultural diffusion. The result that the high ratio of immigrant-style pottery holders need rapid agricultural diffusion supports the assumption that the change of pottery styles is indivisible with agriculture [20]; and 2) in such conditions, immigrant-style pottery had been held mostly by immigrants and had not been widely diffused among native people.

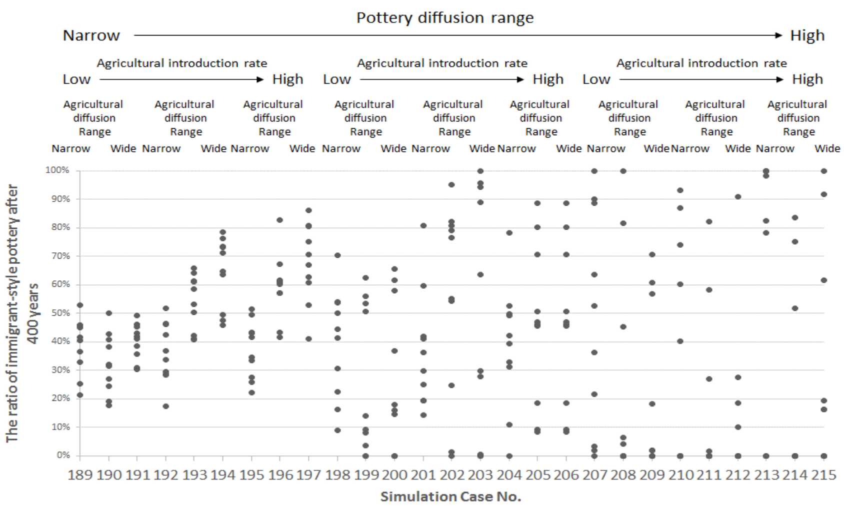

Fig. 6. Difference in the ratio of immigrant-style pottery holders depending on the speed of agricultural diffusion and pottery-style diffusion in the vertical and horizontal transmission of pottery styles in cases of polygamous marriage

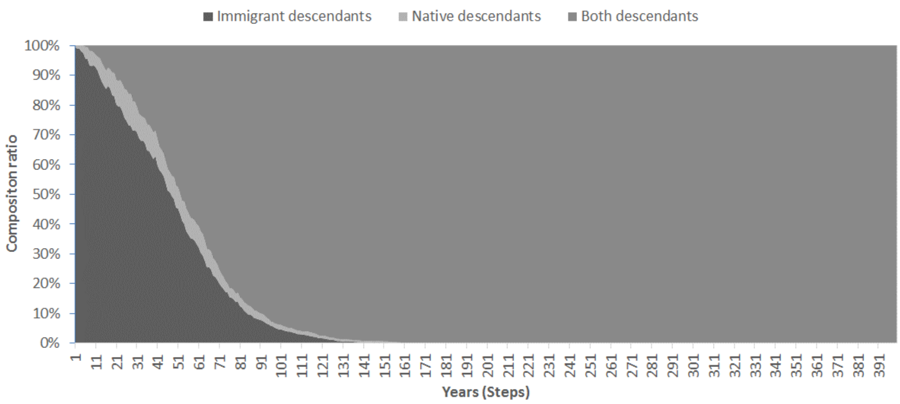

Fig. 7. Composition ratio of each descendant within the immigrant-style pottery holder group in cases of rapid diffusion of agriculture and slow diffusion of pottery styles (Simulation case number 194, Run 9)

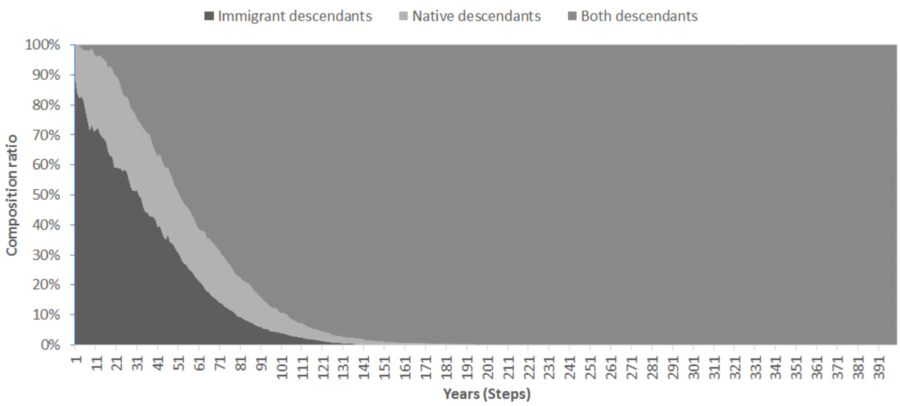

Fig. 8. Composition ratio of each descendant within the immigrant-style pottery holder group in cases of rapid diffusion of agriculture and pottery styles (Simulation case number 215, Run 7)

4 Conclusion

In this paper, we generated new hypotheses about the process of population explosion, agricultural diffusion, and pottery-style diffusion. Although these hypotheses are only hypotheses based on simulation results, they have falsifiability. Specifically, for the process of population explosion and agricultural diffusion, the hypothesis that, during polygamous marriage, agriculture spread rapidly among native people and was, in the early stages, performed mainly by native people could be verified by the discovery of human bone remains of peoples with native traits, along with artifacts verifying the existence of agriculture before and after the start of the Gusuku period. Additionally, for the pottery-style diffusion process, the hypothesis that during polygamous marriage, the high ratio of immigrant-style pottery holders need rapid agricultural diffusion and that the immigrant-style pottery had been held mostly by immigrants and had not been widely diffused among native people would be disproved by the discovery of the bone remains of peoples with native traits, along with immigrant-style pottery before and after the start of the Gusuku period.

Within Japanese anthropology and archaeology, it is difficult to apply the ABSs developed in the famous pioneering studies on factors relating to the residential transition of the Anasazi tribe [21]. As mentioned above, that is because the required data, especially paleo-environmental records, are not widely available. However, in hypothesis generation such as in this study, the hypotheses based on simulation results with falsifiability would be able to facilitate the new discovery of anthropological and archaeological evidence. This study reinforced our assertion that even if there are less data available, ABSs are able to compensate for this paucity of data and generate hypotheses[2]. The technical lmitations of our simulation model is that we only run the limited number of simulations and that we failes to explore the very large parameter space, because of our computational abilities. Mathamatical analyses of our simulation model, such as nonlinear dynamics, may provide us with the further insights on the history simulation studies. These are our future problems.

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