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Rewinding the Dynamics between two Japanese Ancient Descents: -What would happen from the Jomon to the Yayoi Periods in Japan-

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***Abstract*—In this study, through a simple agent-based simulation (ABS) model, we examine the problems experienced by Chinese-Korean immigrants in the formation of the agricultural culture of the Yayoi period (300 BC–250 AD). We focus on two problems: 1) The sex ratio of the immigrants, and 2) who played the major role in agricultural culture in the Yayoi period. The simulation model demonstrates that when most initial immigrants were males and many native Jomon people introduced an agricultural culture in the early stage, it is more probable that the majority of people 300 years later were those with the same traits as the immigrants. These results suggest that the initial immigrants—primarily males—and those who played the major role in the agricultural culture in the early Yayoi period included many native Jomon people. Such results will influence the literature on archaeology.**

I. Introduction

THE Yayoi period (300 BC–250 AD) is the era when rice agriculture began for the first time in Japan about 2,000 years ago. The Yayoi culture was established consequent to the integration of the Jomon culture, a former Yayoi culture, when they lived in the region as hunters and gatherers. it is stated that the agricultural culture was imported from China-Korea. In addition, in anthropological morphology, the human bones of the Yayoi period and Jomon period (14,000 BC–300 BC) differ. Therefore, it is considered that the people from China-Korea had a large genetic influence on the Yayoi people.

Thus, in the formation of the Yayoi culture, when agriculture became the social and economic bases of society, the presence of Chinese-Korean immigrants (Trai-zin in Japanese) was important. However, several problems pertaining to the immigrants remain in Japan's anthropology and archaeology. Specifically, these problems question: 1) the immigrants' place of origin, 2) the initial immigrant population size, 3) the sex ratio of the immigrants, and 4) whether the native Jomon people or immigrants played the major role in the formation of agricultural culture in the Yayoi period.

Regarding the first question, anthropological and archaeological research considers the Korean Peninsula as the immigrants' place of origin. However, for the second question, two hypotheses propose the immigrants' population size as either large or small. The larger immigrant population size is because, as explained, the human bones of the Yayoi period and Jomon period differ. Hanihara [1] estimates that the total immigrant population size over a period of 1,000 years ranged from about 3 million to 10 million people based on a back calculation of the estimated population of the subsequent period. On the other hand, the smaller immigrant population size is because in the beginning of the Yayoi period, the characteristics of pottery and stone tools retain the style of the Jomon period. As such, the size of the immigrant population is not considered large enough to change the characteristics of pottery and stone tools.

Addressing the third question on the sex ratio of the immigrants, a leading hypothesis postulates that the immigrants were primarily male [2]. One reason for this hypothesis is that, as mentioned, the characteristics of pottery and stone tools retain the Jomon style in the beginning of the Yayoi period. This means that if Jomon females made the pottery, then male immigrants mated with native Jomon females. Regarding the immigrant population size, this hypothesis considers that even if the population was large, since the immigrants were primarily males, the characteristics of pottery and stone tools did not change rapidly.

Finally, regarding the fourth question as the most important problem, whether the native Jomon people or Chinese-Korean immigrants played the major role in the formation of agricultural culture in the Yayoi period has been the source of a long controversy. This is an important

research problem pertaining to the anthropology and archaeology of Japan [3]. Some anthropologists advocate that the native Jomon people assimilated the agricultural culture as a new culture, thus playing the major role in Yayoi agricultural culture. As explained, this assertion is because in the beginning of the Yayoi period, the characteristics of pottery and stone tools retained the Jomon style. Based on this, a small immigrant population size is assumed and the major role player in Yayoi agricultural culture is considered the native Jomon people, who comprised the majority of the population. Conversely, some anthropologists insist that the ancient Chinese-Korean people immigrating to Japan brought with them a systematic agricultural culture. As the population grew, their descendants became major role players in Yayoi agricultural culture [4]. This insistence is because the human bones of the Yayoi period and Jomon period differ in anthropological morphology. Based on this, they assume that the immigrant population size was large enough to have a significant impact genetically. Thus, the immigrants played the major role in Yayoi agricultural culture. This dualistic thinking has recently been revised. It is now thought that agricultural society was a collaborative process begun by both the Jomon people and immigrants [3].

To resolve these problems, an examination of population trends and the food production system of the Jomon people and descendants of the immigrants since the agricultural introductory period is needed. However, in the Northern Kyushu region, where agricultural culture began, human bone material from the late Jomon period (1000 BC–300 BC) to the early Yayoi period (300 BC–0 AD) is missing, despite the beginning of agricultural culture during that time.

Among these questions, resolving the problems of the initial immigrant population size and who played the major role in Yayoi agricultural culture, Nakahashi *et al*. [5], [6]—based on discriminant analysis of human bone material—point out that people bearing similar traits to the immigrants accounted for about 80% of the total population in the middle Yayoi period (300 BC–300 AD). Furthermore, using a mathematical equation model, they proposed ancient population dynamics up to the middle Yayoi period. Consequently, when giving the difference in the population growth rate between the native Jomon people and immigrants, they suggested that even a small number of immigrants could account for the large majority a few hundred years later. That is, unlike conventional studies, these studies demonstrated the possibility that even a small initial immigrant population can explain why the human bones of the Yayoi period and Jomon period differ in anthropological morphology. Kataoka *et al*. [4] also estimated the population growth rate based on who inhabited house remains, which was determined by the plan of the house remains, the site location, and the settlement composition. They suggested that only the immigrants could account for the large majority a few hundred years later; therefore, only the immigrants could play the major role in Yayoi agricultural culture. Genetically, these results support the contention that immigrants played the major role in agricultural culture.

These studies are remarkable in that they present objective results through a quantitative approach using mathematical models. However, a few unresolved problems remain. First, these studies are premised on a model in which the native Jomon people and immigrants were partially segregated. Even if a mixed group of Jomon people and immigrants is assumed, a small mixed group population size is estimated with a low ratio of native Jomon people in the group. This assumption is unreasonable if there was no barrier prohibiting marriage and contact, and mating was possible between the Jomon people and immigrants. That is, the effects of random mating between these groups were ignored. Second, they assumed that genetic traits and the food production system were not separated. Therefore, these studies did not consider the diffusion of the food production system. The fertility rate depends on the food production system [7]; thus, it is possible that the population growth rate also depends on subsistence culture. These studies are therefore not able to address the fundamental problem: who played the major role in agricultural culture.

In addition, the problem of the immigrant sex ratio is an important unresolved issue. As mentioned, one leading hypothesis postulates that the immigrants were primarily male, this because in the beginning of the Yayoi period, the characteristics of pottery and stone tools retained the Jomon style. This means that if native Jomon females produced the pottery, then male immigrants mated with native Jomon females. Nakahashi *et al*. [5], [6] calculate that the majority of females in the mixed group comprising native Jomon people and immigrants are Jomon females. However, these studies originally assume a small mixed group; thus, they are unable to estimate the sex ratio of the total immigrants. Furthermore, this hypothesis is inconsistent with the fact that the haplotype frequency of the Jomon people's maternal mitochondrial DNA (mtDNA) differs significantly from that of the Yayoi period people because of the genetic influence from Chinese-Korean people [8]. We therefore believe that the low ratio of immigrant females makes it difficult to change the frequency of mtDNA between Jomon and Yayoi period people. In other words, that in the beginning of the Yayoi period the characteristics of pottery and stone tools retain the Jomon style is inconsistent with the significant changes of the haplotype frequency of mtDNA between Jomon and Yayoi period people. Therefore, the problem of the immigrant sex ratio cannot be resolved through the conventional static model method.

Based on this discussion of previous research, in this study, which is a comparative study of the mathematical model of Nakahashi *et al*. [5], [6], we assume that: 1) at first, a large number of native Jomon people and a small number of Chinese-Korean immigrants coexisted in the Northern Kyushu region, and 2) 300 years later, people bearing the

traits of the immigrants accounted for 80% of the total population. Based on these assumptions, we examined the problem of who played the major role in the Yayoi agricultural culture using agent-based simulation (ABS). The ABS incorporates both random mating and diffusion of the agricultural culture. In addition, we examined the problem of the immigrant sex ratio by adding the pottery style and mtDNA inheritance models to our simulation model.

II. Simulation Model

A. Description of the Model

Our simulation model is described according to Overview, Design concept, and Details (ODD) protocol [9], [10]. The protocol is intended to address the criticism that agent-based models lack reproducibility. Furthermore, it aims at improving the integrity and standardization of description.

B. Agent and State Variables

The agent is an ancient person and has the following variables.

1. ID number and spatial placement

The agent has an "ID number" and "Coordinate position [*X*, *Y*]" information respectively in a two-dimensional space. In our simulation model, space is not real space but an abstract space, because our study mainly treats the relative diffusion between agricultural culture and trait genes. Therefore, the size of space in our simulation is defined by the speed of diffusion of agricultural culture as described below.

2. Sex

The agent is "Male" or "Female."

3. Life expectancy and Age

The agent is given a "Life expectancy" based on the table of mortality when the agent is created (born). If the "Age" of the agent is greater than the life expectancy, the agent is removed (dies). We created the table of mortality to reflect the infant mortality rate until recent years of 20% into the mortality table of the Jomon people [11]. We also presume in our simulation model that the mortality table is the same for the Yayoi and Jomon people.

4. Food production system

The food production system variable for the agent is "Hunting and Gathering" or "Agriculture." The food production system changes from "Hunting and Gathering" to "Agriculture" through the diffusion of agriculture assuming that the cold climate from the late Jomon to early Yayoi period introduced the opportunity for this conversion.

5. Institution of marriage

The institution of marriage variable for the male agent is "Monogamous" or "Polygamous." The institution of marriage for the Jomon period is unknown. However, for the Yayoi period, polygamous marriage is assumed based on descriptions in "Gishi-Wazin-Den," which was written by the ancient Chinese on Yayoi period customs: There are some males of high status who have four or five wives, and even some males of normal status who have two or three wives. We postulate that sustaining more than one wife—polygamous marriage—requires a surplus of food. Therefore, in our simulation model, if the male agent includes both "Polygamous" and a high food production system "Agriculture," then the agent marries three female agents. A new agent (child) inherits the institution of marriage from the father agent.

6. Pottery style

The pottery style variable is either "Jomon style" or "Immigrant style." Considering the hypothesis that females made the pottery, a new agent (child) inherits the pottery style from the mother agent in our simulation model.

7. Trait genes

The trait gene determines trait characteristics. Originally, it was thought that trait characteristics are determined by involving many genes in a complex manner. However, to simplify this for the simulation, in our simulation model, following Nakahashi *et al*. [5], [6], it is assumed to be composed of major pair alleles. The alleles comprise the "Jomon-type gene (J)" and "Immigrant-type gene (T)." When a new agent (child) is created (born), the agent inherits either of the father agent's alleles and either of the mother agent's alleles. In other words, the combination of alleles of an agent is "JJ," "TT," or "JT." According to these combinations, each agent is classified as one with Jomon people or immigrant traits. Specifically, a "JJ" agent comprises traits of the Jomon people, a "TT" agent comprises immigrant traits, and a "JT" agent displays mixed traits (mixed people). In addition, mixed people are determined as those comprising immigrant traits at a given ratio.

8. MtDNA macrohaplogroup

The mtDNA haplogroup variable for an agent is "macrohaplogroup N" or "macrohaplogroup M." The mtDNA is the cell organelle DNA of mitochondria, is inherited maternally, and is relatively easy to extract from human bone remains. Therefore, mtDNA analysis is a useful way to investigate the origin of the maternal line of ancient people. The mtDNA of people in East Asia is broadly classified into macrohaplogroup N or macrohaplogroup M [12], [13]. Results of mtDNA analysis of human bone remains were recently accumulated in Japan. A major difference between Jomon and Yayoi period people is evident in the frequency of mtDNA macrohaplogroup N and M [8]. Specifically, for Jomon period people, the frequency of mtDNA macrohaplogroup N is about 50%, and about 50% for the macrohaplogroup M. On the other hand, for Yayoi period people, the frequency of mtDNA macrohaplogroup N is about 20%, while macrohaplogroup M is about 80%. In our simulation model, when a new agent (child) is created (born), the agent inherits the mtDNA macrohaplogroup from the mother agent as described below.

C. Process Overview and Scheduling

Our simulation model proceeds in an annual time step. In our simulation model, the annual time step is a year. Each year, the three sub-models of each agent are executed in turn as follows: Diffusion of agricultural culture rule, Marriage rule, and Moving rule. In addition, each agent is processed in a random order within each year.

D. Design Concepts

Our simulation model corresponds to 7 of the 11 design concepts of ODD protocol (Table I). Our simulation model is simple, thus, we think that the description of the model and design concepts in this paper is sufficient to indicate reproducibility.

TABLE I.
DESIGN CONCEPTS

No.	Design concepts	Elements
1	Basic Principles	Trait gene was diffused by the increase of population based on the food production system under the diffusion of agricultural culture ・For the diffusion of the food production system, we apply the infection model (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 composition ratio of each trait gene type of agricultural culture holder, the diffusion rate of Jomon-style pottery and the frequency of mitochondrial DNA macrohaplogroup M
3	Adaptation	If an agent is near the other agent with agricultural culture, it introduces an agricultural culture in a given rate
4	Sensing	・Recognizing whether a male agent is near the other agent with agricultural culture ・Recognizing whether an agent is near the female agent
5	Stochasticity	・Life expectancy ・Spatial placement ・Mitochondrial DNA macrohaplogroup ・Introduction of agriculture ・Selection of female agent for marriage ・Sex of child agent ・Combination of trait gene ・Move in random direction
6	Collectives	Number of agents created is determined by the number of agents with "hunting and gathering" and "agriculture"
7	Observation	・Ratio of people with immigrant trait ・Diffusion rate of agricultural culture ・Composition ratio of each trait gene type of agricultural culture holder ・Diffusion rate of Jomon-style pottery ・Frequency of mitochondrial DNA macrohaplogroup M

E. Sub-models

1. Diffusion of agricultural culture rule

Agricultural culture is diffused from a neighboring other agent and through inheritance from a parent agent. In the case of diffusion from a neighboring other agent, if the agent's food production system is "Hunting and Gathering," from all the neighboring other agents with "Agriculture" within given radius cells, the agent's food production system will be "Agriculture" based on given probability. Conversely, in the case of inheritance from a parent agent, by the marriage rule described below, when a new agent (child) is created (born), the agent inherits the food production system from the father or mother agent. In this study, inheritance from the father or mother agent is simulated.

2. Marriage rule

A new agent (child) is created (born) by the marriage of a male and female agent. The male agent is married to a female agent randomly selected from all female agents within three surrounding cells. Furthermore, a new agent is created according to the population growth rate of the mother agent's food production system. The new agent is created at the same spatial placement as the mother agent. The sex of the new agent is allocated as male and female with a 50% probability, and the new agent has a life expectancy and 0 age. For the trait gene, as explained, the new agent inherits either of the father agent's alleles and either of the mother agent's alleles. In addition, the new agent inherits the food production system from father or mother agents, the institution of marriage from the father agent, and pottery style and mtDNA macrohaplogroup from the mother agent. Moreover, as mentioned, only when the male agent is both "Polygamous" and "Agriculture," the male agent can be married to three female agents.

3. Moving rule

Within each step, an agent moves one cell in random directions in a space of the simulation.

F. Initialization

1. Time span of simulation

The time span of our simulation is 300 years (300 steps) from the early Yayoi period to the middle Yayoi period. This value is the same as that of the representative example of

calculation in Nakahashi *et al*. [5]. While, as the result of Accelerator Mass Spectrometry (AMS) radiocarbon dating, a new hypothesis postulates the start of the Yayoi period as 500 years earlier than conventional hypotheses, no clear conclusions have yet been reached. Therefore, in this study, the time span is 300 years, which is a more stringent condition for the demographic transition in which the small size of the immigrant population could account for the large majority a few hundred years later.

2. *Population growth rate based on the food production system*

The population growth rate of the agriculture people is higher than that of the hunting and gathering people. We simulate the two cases for the growth rate of each population as follows. Each population growth rate for the first case (high rate case) has the same value as that of the representative calculation example in Nakahashi *et al*. [5]. Each population growth rate for the second case (low rate case) has the lowest value in Nakahashi *et al*. [5].

First case (high rate case): the population growth rate of hunting and gathering people is 0.1% per year, while agriculture is 1.3% per year.

Second case (low rate case): the population growth rate of hunting and gathering people is 0.1% per year, while agriculture is 0.5% per year.

3. *Speed of the diffusion of agricultural culture*

The speed of the diffusion of agricultural culture in our simulation comprises the range of cells of the diffusion and introduction rate. The range of cells of diffusion corresponds to the distance for cultural exchange to occur while in contact with each other; thus, we assumed three degrees: "Narrow (1 cell)," "Moderate (3 cells)," and "Wide (5 cells)." The introduction rate corresponds to the difficulty of introducing an agricultural culture; thus, we assumed four degrees: "Impossible (0%)," "Difficult (0.1%)," "Medium (0.5%)," and "Easy (1%)." This level of difficulty does not refer to the difficulty of agricultural techniques, but to an adequate environment and culture needed to accept the agricultural culture as a new culture. These values are set assuming that even when the range of cells is "Narrow" and the introduction rate is "Difficult," approximately 300 years are needed for the most agents to have "Agriculture."

4. *Inheritance of the food production system from a parent*

The inheritance of a food production system from a parent is unknown. Therefore, to investigate the extent of the simulation result impacted by inheritance either from the father or mother, we simulate the two cases as follows.

First case (father): a new agent (child) inherits the food production system from the father agent.

Second case (mother): a new agent inherits the food production system from the mother agent.

5. *State variables of the initial Jomon people and immigrants*

The simulation run starts with the initial Jomon people and immigrants, the state variables of which are described below.

a) Initial Jomon people

Trait gene: "JJ"
Food production system: "Hunting and gathering"
Institution of marriage: "Monogamous"
Pottery style: "Jomon style"
MtDNA macrohaplogroup: Referring to Shinoda [8], 50% have "macrohaplogroup N" and 50% have "macrohaplogroup M."

b) Initial immigrants

Trait gene: "TT"
Food production system: "Agriculture"
Institution of marriage: "Monogamous" or "Polygamous" in each simulation case
Pottery style: "Immigrant style"
MtDNA macrohaplogroup: In total, 62.5% have "macrohaplogroup M" and 37.5% have "macrohaplogroup N." The haplogroup frequency of the immigrants' mtDNA is unknown. However, because it is thought that the immigrants arrived via the Korean Peninsula, in this study, the frequency of macrohaplogroup of the current people of the Korean Peninsula [8] is used as that of the immigrants.

6. *Spatial placement of the initial Jomon people and immigrants*

It is assumed that the initial immigrants arrived from northern coastal areas at the earliest stage. Therefore, in this study, the initial immigrants are densely positioned on one point at the start of the simulation run. To investigate the extent of the simulation result impacted by this assumption, we simulate the two cases in the spatial placement of the initial Jomon people and immigrants as follows.

First case (dense distribution): the initial Jomon people are uniformly randomly placed, while the initial immigrants are placed on the center of the upper side of space [*X: 25, Y: 50*], assuming that they came from the northern coastal area.

Second case (dispersed distribution): Both the initial Jomon people and initial immigrants are uniformly randomly placed.

7. *Number of initial Jomon people and immigrants*

The number of initial Jomon people is 200 agents and immigrants 1,800 agents, referring to the ratio of 9:1 of initial Jomon people and immigrants in the representative calculation example in Nakahashi *et al*. [5].

8. *Sex ratio of initial Jomon people and immigrants*

As mentioned, a leading hypothesis states that the immigrants were primarily male. Therefore, to discuss the sex ratio of initial immigrants, we simulate three cases in the initial immigrants' sex ratio as follows. In contrast, the male and female ratio of initial Jomon people is equal.

First case (same): the number of males for initial immigrants is 100 agents and the number of females is 100 agents.

Second case (more): 150 male agents and 50 female agents

Third case (majority): 175 male agents and 25 female agents

9. Ratio determining "JT" mixed people as those with immigrant traits

If agents are mixed people with the "JT" trait gene, then they display immigrant traits at the given ratio. We simulate two cases for this ratio as follows.

First case (100%): people with immigrant traits at a ratio of 100%

Second case (50%): people with a 50% ratio of immigrant traits

In the first case, they are determined as immigrants based on the assumption that a person with even a small amount of immigrant traits has immigrant traits.

G. Number of Simulation Cases and Evaluation Index

The total number of simulation cases is 441 cases. This figure refers to cases combining each of the above parameters (Table II) added to the representative example of a simple increase of calculation in Nakahashi *et al*. [5]. The simple increase of calculation is a model based on the assumption that the number of Jomon people and immigrants increased separately without random mating and cultural exchange between them.

For the number of simulation runs, cases combining "agricultural population growth rate: 1.3%" and "spatial placement of the initial Jomon people and immigrants: dispersed distribution" were run once, considering computational costs. The other cases were run ten times. The random seed value of these ten runs was the same among cases.

The main evaluation index in our simulation results was the ratio of people with immigrant traits within all agents. It was reported [5] that with regard to demographic transition in the middle Yayoi period, the ratio of people with immigrant traits was 80% or more. Therefore, determining if the ratio 300 years later (steps) is close to 80% or more is a measure of demographic transition in our simulation. In this study, we refer to the ratio for each run of each case. In addition, in the simulation case where demographic transition occurred, to discuss who played the major role in Yayoi agricultural culture, we illustrate a time series of the diffusion rate of agricultural culture and composition ratio of each trait gene type of agricultural culture holder. Moreover, the diffusion rate of Jomon-style pottery and the frequency of mtDNA macrohaplogroup M are compared among these cases. For the diffusion rate of Jomon-style pottery, considering that in the beginning of the Yayoi period the characteristics of most pottery retained the Jomon style, we investigate if the diffusion rate of Jomon-style pottery is higher. Furthermore, with regard to the frequency of mtDNA macrohaplogroup M, considering that the frequency of macrohaplogroup M of the Yayoi period people was about 80%, we determine whether the frequency of macrohaplogroup M is higher.

III. Results and Discussion

Of the 441 cases, 111 demonstrated a more than 80% ratio of people with immigrant traits 300 years later (steps).

In the case of the representative example of a simple increase of calculation in Nakahashi *et al*. [5], the ratio of people with immigrant traits was 78.9%. This case is without random mating and cultural exchange between the native Jomon people and immigrants.

In the following sections, when referring to random mating and cultural exchange between the Jomon people and immigrants, we refer to differing results in the cases of "spatial placement of initial immigrants," "institution of marriage," "speed of the diffusion of agriculture," and "sex ratio." As such, we describe only results of cases common in "inheritance of food production system from a parent: mother" and "ratio determining "JT" mixed people as those with immigrant traits: 100%."

A. Spatial Placement of Initial Immigrants

In cases where both the initial Jomon people and initial immigrants are uniformly randomly placed, the ratio of

TABLE II.
VALUES OF PARAMETERS

Initialization parameters	Values
Time span of simulation	[300 years(steps)]
Population growth rate of hunting and gathering people	[0.1%]
Population growth rate of agricultural people	[1.3%], [0.5%]
Range of cells of the diffusion	[Narrow: 1 cell], [Moderate: 2 cells], [Wide: 3 cells]
Introduction rate of agricultural culture	[Impossible : 0%], [Difficult : 0.1%], [Middle : 0.5%], [Easy : 1.0%]
Inheritance of food production system from a parent	[Father], [Mother]
Institution of marriage of the initial Jomon people	[Monogamous]
Institution of marriage of the initial immigrants	[Monogamous], [Polygamous]
Spatial placement of the initial Jomon people	[Dispersed distribution]
Spatial placement of the initial immigrants	[Dispersed distribution], [Dense distribution]
Sex ratio of the initial immigrants (Male, Female)	[Same: 100, 100], [More: 150, 50], [Majority: 175, 25]
Sex ratio of the initial Jomon people (Male, Female)	[900, 900]
Ratio determining the mixed people as those with immigrant traits	[100%], [50%]

people with immigrant traits does not reach 80%, then that is considered a measure of demographic transition (Fig. 1, Fig. 2). Generally, cases where the speed of diffusion of agricultural culture is slow (e.g. the range of cells of diffusion: "Narrow [1 cell]" and the introduction rate: Difficult [0.1%]) indicate a higher ratio of people with immigrant traits. On the other hand, cases where the speed of diffusion of agricultural culture is rapid (e.g. the range of cells of diffusion: "Wide [5 cells]" and the introduction rate: Easy [1%]) indicate a lower ratio of people with immigrant traits.

For the dense distribution of immigrants, some cases attain the 80% ratio of people with immigrant traits 300 years later as a measure of demographic transition (Fig. 3, Fig. 4). The immigrants in these cases are all "Polygamous." We provide more information on these cases in the following sections.

The reason demographic transition does not occur in the case where both the initial Jomon people and immigrants are uniformly randomly placed is because there are many points of agricultural culture diffusion. Agricultural culture is diffused among the native Jomon people at the early stage, and the Jomon population increases at the high rate of agricultural people. Therefore, even in the case where the population growth rate of agricultural people differs, the same result is shown (Fig. 3, Fig. 4). To generate demographic transition, our results show the probability that the immigrants lived at high population densities and that only a part of the neighboring native Jomon people made contact with them.

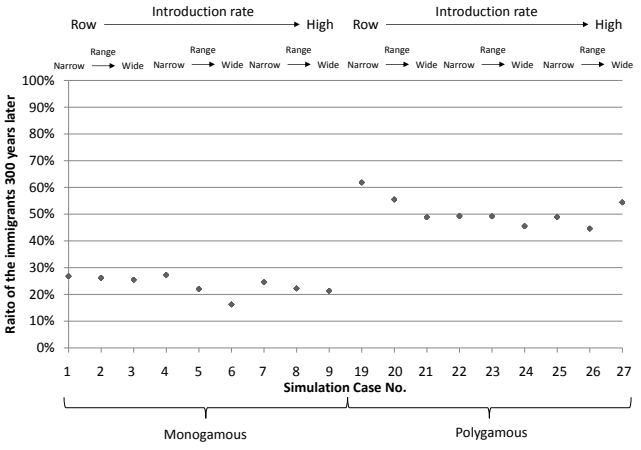

Fig. 1 Ratio of people with immigrant traits 300 years later in the cases of dispersed distribution and a 1.3% agricultural population growth rate

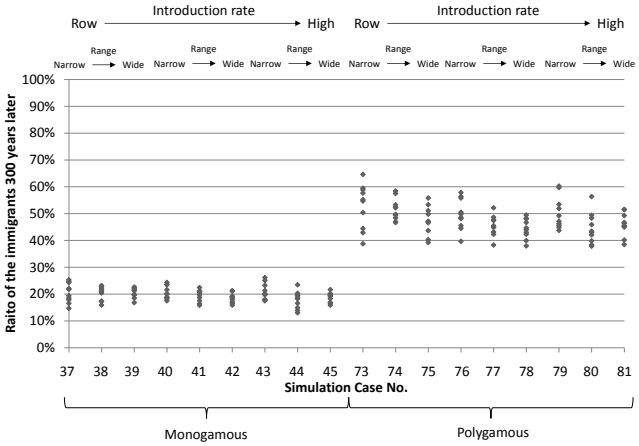

Fig. 2 Ratio of people with immigrant traits 300 years later in the cases of dispersed distribution and a 0.5% agricultural population growth rate

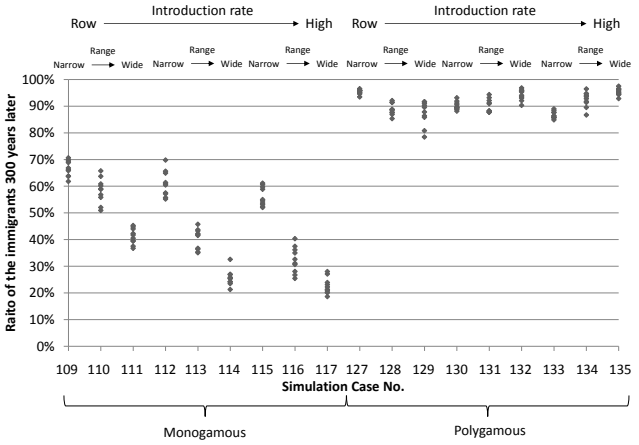

Fig. 3 Ratio of people with the immigrant traits 300 years later in the cases of dense distribution and 1.3% of agricultural population growth rate

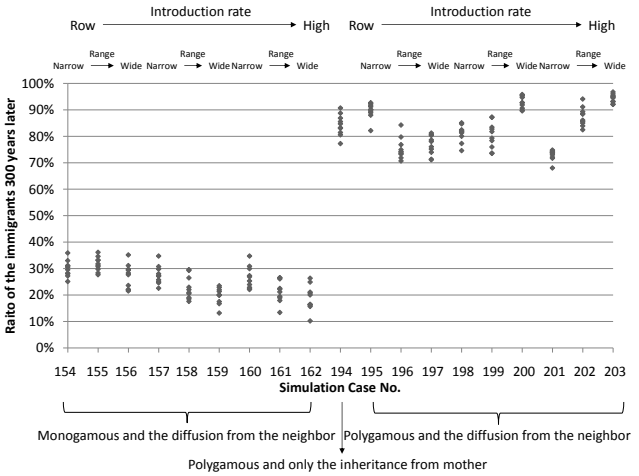

Fig. 4 Ratio of people with immigrant traits 300 years later in the cases of dense distribution and a 0.5% agricultural population growth rate

B. Institution of Marriage and Speed of Agricultural Diffusion

1. Cases of monogamous marriage and diffusion from neighboring other agents

In cases of the dense distribution of immigrants, the monogamous marriage and the diffusion of agriculture from neighboring other agents, the ratio of people with immigrant traits 300 years later does not attain the 80% needed to indicate demographic transition (Fig. 3, Fig. 4). The reason is the same as described earlier. Once agricultural culture diffused among the native Jomon people at the early stage, their population increased at the high rate of agricultural population growth. Therefore, also in these cases, cases in which the diffusion of agricultural culture is slow indicate a higher ratio of people with immigrant traits, while cases with rapid diffusion of agricultural culture evidence a lower ratio of people with immigrant traits. Considering these results, even if assumed that marriage would take place preferentially within the population, because the agricultural culture is diffused among native Jomon people when the trait gene is diffused only within the population, demographic transition would not have occurred.

2. Case of polygamous marriage and only inheritance from a parent agent

In the case of the polygamous immigrants where agricultural culture is only inherited from a parent agent (not diffused from a neighboring other agent), even when the agricultural people's population growth rate is 0.5% of the lower rate, in some cases the ratio of immigrants 300 years later attains 80% (Fig. 4). If the initial immigrants were "polygamous," demographic transition is probable. In addition, considering these results, even if the agricultural people's population growth rate was lower, it would be enough to infer that demographic transition occurred. That is, demographic transition in which people with immigrant traits came to account for the majority a few hundred years later could occur by the diffusion of the trait gene in polygamous marriage assuming a low population growth rate for the agricultural people. Given that agricultural technology was not mature at that time, a 1.3% population growth rate for agricultural people may be too high. Therefore, these results indicate a high consistency for demographic transition even when the agricultural people's population growth rate is low. In addition, as described above, when employing the hypothesis that the start of the Yayoi period was 500 years earlier, even the lower rate of population growth could generate demographic transition.

However, in these cases, the diffusion rate of agricultural culture 300 years later is very low (about 25%), because agricultural culture is inherited only from either father or mother. Moreover, the composition ratio of each trait gene type of the agricultural culture holder is the immigrant-type "TT" or mixed-type "JT." Therefore, when people with the mixed-type "JT" are determined as those with immigrant traits at a ratio of 100%, they would dominate agricultural culture, meaning it is not diffused among those with Jomon people traits.

3. Case of polygamous marriage and diffusion from the neighboring other agent

In the case with the polygamous immigrants and agriculture that is not only inherited from a parent agent but also diffused from the neighboring other agent, the ratio of people with immigrant traits 300 years later varies depending on the speed of the diffusion of agricultural culture. When the population growth rate of the agricultural culture people is 0.5% of the lower rate, some slow-speed agricultural culture diffusion cases do not attain the 80% ratio of people with immigrant traits 300 years later (Fig. 4). In contrast, in cases demonstrating significant speed in agricultural culture diffusion, the 80% ratio of people with immigrant traits 300 years later is attained. When the population growth rate of the agricultural people is 1.3% of the higher rate, regardless of the speed of agricultural culture diffusion, the ratio of people with immigrant traits 300 years later attains 80% in all cases (Fig. 3). Even so, the rapid speed of agricultural culture diffusion is higher in the ratio of people with immigrant traits 300 years later.

These results demonstrate that in the case of polygamous marriage and the diffusion of agriculture, the wider diffusion of agricultural culture more easily generates demographic transition. The reason is that there is a time lag between the diffusion of agricultural culture and polygamous marriage, and this time lag influences the increasing population of the Jomon people and immigrants. Specifically, the dense distribution of immigrants means that the number of immigrants increased at the earliest stage, and in this process, agricultural culture diffused among the Jomon people. However, polygamous marriage remained an immigrant trait as it was inherited from the father. Consequently, the neighboring Jomon people came to have an agricultural culture. Furthermore, in the situation where the immigrants' neighbors with an agriculture culture display a higher population growth rate, the immigrant trait gene type is diffused through polygamous marriage. In other words, it is necessary for the wider diffusion of the immigrant trait gene type that the immigrants' neighbors demonstrating an agricultural culture display a higher population growth rate.

As for the composition ratio of each trait gene type of agricultural culture holder in these cases, in slow agricultural culture diffusion cases, at the early stage, those with the Jomon-type "JJ" and the immigrant-type "TT" were slightly mixed. The mixed-type "JT" then came to account for most agricultural culture holders by marriage (Fig. 5). On the other hand, in cases demonstrating significant rapid agricultural culture diffusion and demographic transition, at the earliest stage, agricultural culture holders were only those with the immigrant-type "TT." However, shortly thereafter, those with the Jomon-type "JJ" became the majority (Fig. 6). Following that, the mixed-type "JT" became the most

through marriage. These results show the probability that even if agricultural culture was widely diffused among the Jomon people, demographic transition could be generated.

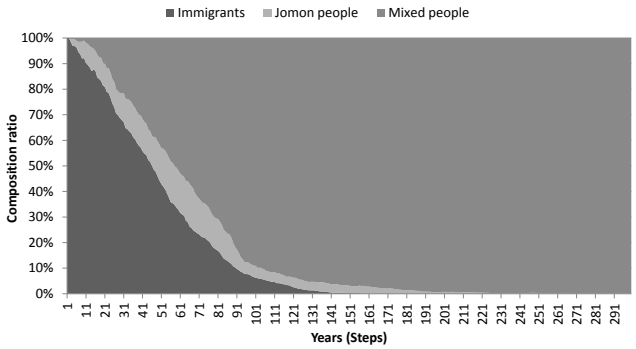

Fig. 5 Composition ratio in agricultural culture holders (No. 196)

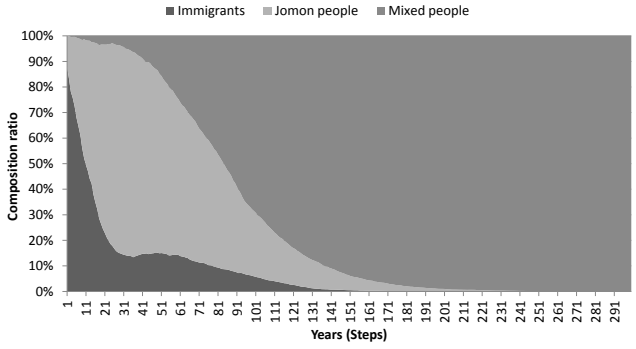

Fig. 6 Composition ratio in agricultural culture holders (No. 203)

C. Sex Ratio of Initial Immigrants

With regard to the sex ratio of initial immigrants, regardless of the population growth rate of the agricultural people and the inheritance of agriculture either from father or mother, generally, cases where the immigrants are primarily male demonstrate a slightly higher ratio of people with immigrant traits 300 years later than cases comprising equal numbers of males and females. In addition, in the ratio of Jomon pottery 300 years later, there are slightly more cases in which immigrants are primarily male, this being close to archaeological fact (Fig. 7, Fig. 8, Fig. 9). However, in the frequency of the mtDNA macrohaplogroup, there is no clear difference between cases where immigrants are primarily male and cases with equal numbers of males and females (Fig. 10, Fig. 11, Fig. 12). The reason is that the frequency of the mtDNA macrohaplogroup is largely influenced by random genetic drift. Conversely, these results show that when the immigrants are primarily male, the haplogroup frequency of the maternal mtDNA could significantly change. Our results find that even when the number of female Jomon people is one-tenth of the female immigrants, when the number of immigrants is increased, the frequency of mtDNA macrohaplogroup changes significantly. Based on this, with regard to the sex ratio of the initial immigrants, higher consistency is evident when immigrants are primarily male. That is, our simulation results support the hypothesis that the immigrants were primarily male.

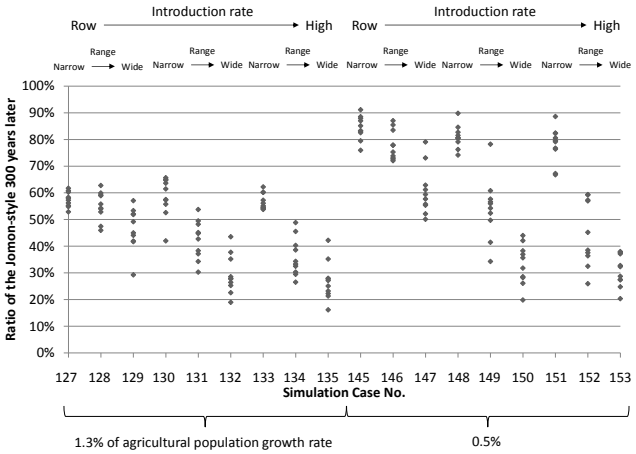

Fig. 7 Ratio of Jomon-style pottery 300 years later in cases comprising equal numbers of males and females

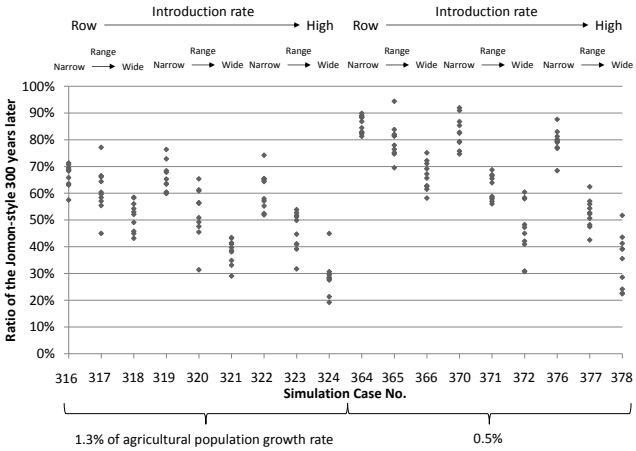

Fig. 8 Ratio of Jomon-style pottery 300 years later in in the cases where male is the more

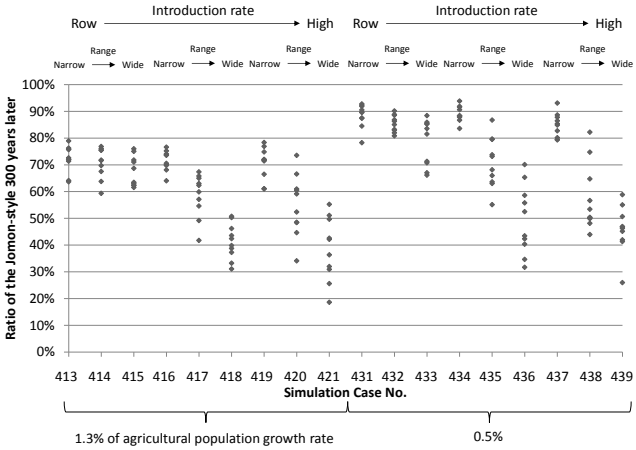

Fig. 9 Ratio of Jomon-style pottery 300 years later in the cases where male is the majority

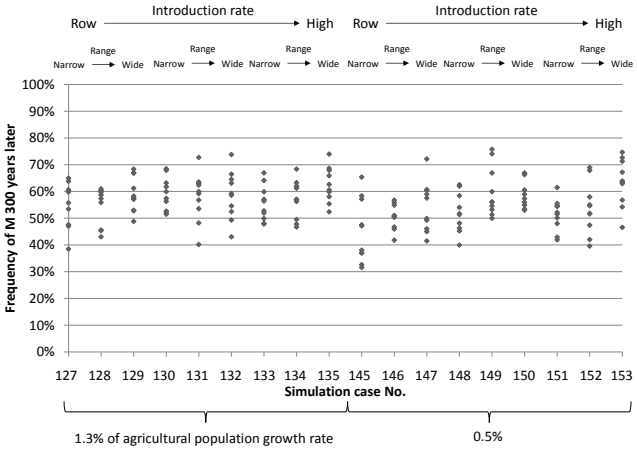

Fig. 10 Frequency of macrohaplogroup M 300 years later in cases comprising equal numbers of males and females

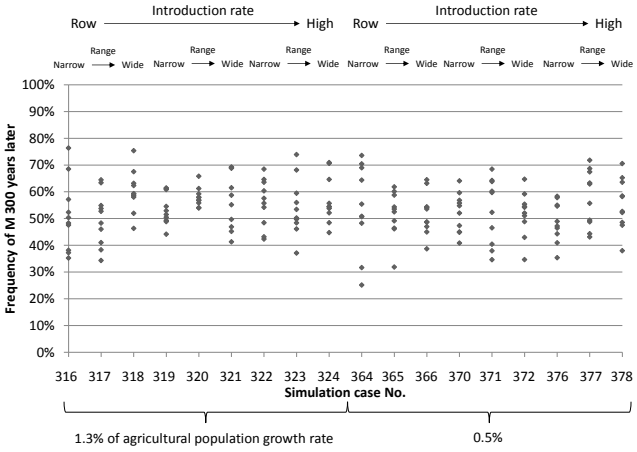

Fig. 11 Frequency of macrohaplogroup M in 300 years later in the cases where male is the more

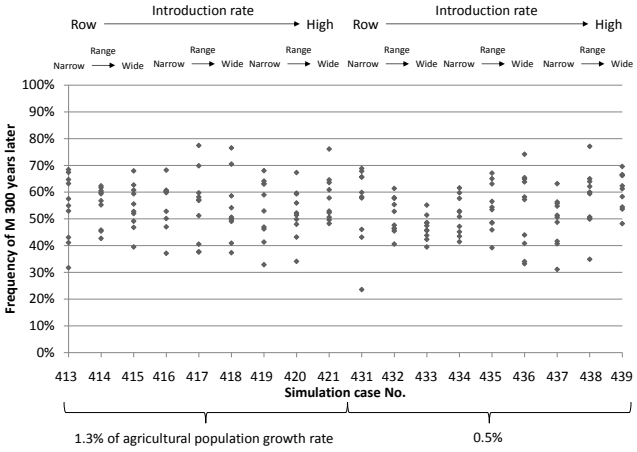

Fig. 12 Frequency of macrohaplogroup M in 300 years later in the cases where male is the majority

D. Who Played the Major Role in the Formation of Agricultural Cultures?

With regard to the problem of who played the major role in the formation of agricultural cultures in the Yayoi period, in the case where a large number of native Jomon people and a small number of immigrants at first coexisted, and where people with immigrant traits came to account for 80% of the total a few hundred years later, our simulation results show the three probable cases described above. In the first case, the immigrants are polygamous and the agricultural culture is only inherited from a parent agent (not diffused from the neighboring other agent). In this case, agricultural culture holders at the early stage are those displaying immigrant or mixed people traits. In this case, the immigrants played the major role in the formation of agricultural culture. In the second case, the immigrants are polygamous and agricultural culture is either inherited from a parent agent and diffused from the neighboring other agent. However, agricultural culture diffusion is slow. In this case, the agricultural culture holders at the early stage comprise many immigrants and few Jomon people. Here, as for the first case, immigrants played the major role in the formation of agricultural culture. In the last case, agricultural diffusion is significantly rapid. In this case, the majority of agricultural culture holders are the immigrants at the earliest stage, but shortly thereafter, become the Jomon people at the early stage. Here, few immigrants and many Jomon people played the major role in the formation of agricultural culture.

Of these three probable cases, the last is most consistent with anthropological and archaeological fact for the following reasons. In the first case, the diffusion rate of agriculture is too low. Considering that the diffusion of agricultural culture began from the North Kyushu region, it is difficult to assume that the diffusion rate at the place of the origin of agriculture in Japan was low. Comparing the second and last case, even when the population growth rate of agriculture is high, the rapid speed of agricultural culture diffusion is higher in the ratio of people with immigrant traits 300 years later. In addition, when the population growth rate of agricultural people is low, in cases demonstrating slow agricultural culture diffusion, some do not attain the 80% ratio of immigrants 300 years later. As mentioned, considering that agricultural technology was not mature at that time, the 1.3% population growth rate of agricultural people may be too high. Therefore, the highest consistency is found in cases where even the lower population growth rate could generate demographic transition through rapid agricultural culture diffusion.

However, when investigating the ratio of Jomon-style pottery 300 years later, there are more cases of slow agricultural culture diffusion than cases demonstrating rapid diffusion (Fig. 7, Fig. 8, Fig. 9). This is because in cases of slow agricultural diffusion, there is a longer time to increase the prevalence of immigrant-style pottery; thus, the ratio of immigrant-style pottery increases. In our simulation model, only the vertical spread of the inheritance of pottery style from the mother is considered. The horizontal spread of diffusion from the neighbor is not considered. However, even if the vertical spread of pottery style is considered in our simulation model, it goes without saying that this

simulation model shows a higher ratio of Jomon-style pottery 300 years later than the model described in this study. Much remains unknown with regard to the manner of diffusion of pottery style; thus, our simulation model is not enough and leaves room for improvement.

However, important is that even when only the inheritance of pottery style from the mother is included, our simulation results indicate a majority Jomon-style pottery 300 years later. That is, our simulation results are consistent with anthropological and archaeological fact that people with immigrant traits became the majority, while conversely; the Jomon-style pottery retained its majority.

IV. Concluding Remarks

We described the ABS and discussed its meaning in historical and archaeological literature. In previous sections, to facilitate understanding of the factors affecting the behavior of the simulation results, the simple model and extreme settings were presented. However, in the case where a large number of native Jomon people and a small number of immigrants at first coexisted, people with immigrant traits became the majority a few hundred years later. As such, several hypotheses are verified and a novel hypothesis proposed. The former refers to hypotheses that the immigrants lived at high population densities and only a part of the neighboring native Jomon people made contact with them, and that the immigrants were polygamous and primarily male. The latter is the hypothesis that when agricultural culture diffused among the native Jomon people, the few immigrants and many Jomon people played the major role in the formation of agricultural culture.

Regarding the hypothesis that the immigrants lived at high population densities and only a part of the neighboring native Jomon people made contact with them, no archaeological evidence yet indicates an immigrant-only colony [3], [5]. However, our results regarding this hypothesis could also be explained by the possibility that an extremely low population density of Jomon people at the time resulted in the settlement of immigrants there [4]. This is also supposed by the possibility that the Jomon population significantly decreased, as evident in the small number of remains of the late Jomon period [14].

Advances in DNA analysis and further excavation in the future could verify hypotheses that immigrants were polygamous and primarily male, and the novel hypothesis that when agricultural culture diffused among the native Jomon people, a few immigrants and the many Jomon people played the major role in the formation of agricultural culture. Hypotheses that the immigrants were polygamous and primarily male cannot be directly verified, but could be indirectly verified by investigating the genetic diversity of the paternal Y chromosome of ancient human bone remains.

Discovering the bone remains of people with Jomon traits along with artifacts showing the existence of agricultural culture could support the hypothesis that when agriculture diffused among the native Jomon people, a few immigrants and many Jomon people played the major role in the formation of agricultural cultures. In fact, although agricultural artifacts have not been discovered, human bone remains with Jomon people' characteristics were discovered at a Korean-type tomb at the Otomo site in Northern Kyushu.

For the problem of who played the major role in the formation of agricultural culture in the Yayoi period, our simulation results indicate that the few immigrants and many Jomon people fulfilled this role. This shows that within the framework where even a small number of immigrants generated demographic transition [5], [6], the idea that agricultural society was a collaborative process begun by both Jomon people and immigrants making a living population [3] has a high consistency.

As points of attention, the hypotheses in this study have shown only some probabilities. The results of our simulation were generated through a model based on several assumptions. The results could change if employing different assumptions. In addition, the ratio of immigrants 300 years later, a prerequisite of our simulation, relied on the results of Nakahashi *et al*. [5]. Therefore, if the discriminant used in their study varies, a different interpretation of the results of our study is required. By the way, demographic transition may be caused by plague and war in addition to a differing population growth rate; however, because there is no archaeological evidence, these are not considered in our simulation model [5].

Finally, we believe that the ABS model and results of this study are widely applicable beyond the time and region, because this study dealt with the universal themes of population dynamics after introducing agricultural culture. Furthermore, this study is the first application of ABS to the problem of anthropology and archaeology in Japan. For the problem of Japan's anthropology and archaeology, it is difficult to use the ABS used in famous pioneering studies on factors regarding the residence transition of the Anasazi tribe [15]. In most anthropology and archaeology cases in Japan, the data, especially paleo-environmental records, are not present in abundance unlike in these studies. However, even if there are less data as in this study, ABS is able to compensate; therefore, it has the potential to become a powerful tool in anthropology and archaeology in Japan.

References

[1] K. Hanihara, "Estimation of the number of early migrants to Japan: A simulative study," *Anthropological Science*, vol. 95, pp. 391-403, 1987.

[2] T. Kaneseki, *Nihonminzoku no kigen*, Hosei, University Press, 1976.(in Japnanese)

[3] S. Fujio, "The Formation of Yayoi Culture in Fukuoka Plain: The interaction between Hunter-gatherers and Agrarian," B*ulletin of the National Museum of Japanese History*, vol. 77, pp.51-84, 1999. (in Japanese with English abstract)

[4] K. Kataoka, and M. Iizuka, "A mathematical study of the increase of the "Yayoi migrant population"", *Kyushu Koukogaku*, vol. 81, pp.1-20, 2006. (in Japanese with English Abstract)

[5] T. Nakahashi, and M. Iizuka, "Anthropological Study of the Transition from the Jomon to the Yayoi Periods in the Northern Kyushu Using Morphological and Paleodemographical Features," *Anthropological science. Japanese series*, vol. 106, pp. 31-53, 1998. (in Japanese with English abstract)

[6] T. Nakahashi, and M. Iizuka, "Anthropological Study of the Transition from the Jomon to the Yayoi Periods in the Northern Kyushu Using Morphological and Paleodemographical Features (2),"*Anthropological science. Japanese series*, vol. 116, pp. 131-143, 2008. (in Japanese with English abstract)

[7] G. R. Bentley, G. Jasinenska, and T. Goldberg, "Is the Fertility of Agriculturalists Higher Than That of Nonagriculturalists?," *Current Anthropology*, vol. 34, pp. 778-785, 1993.

[8] K. Shinoda, "Idenshi de saguru Nihonjin no naritachi", *Nihonrettutou no shizenshi*, Edited by National Science Museum, pp. 296-307, 2006. (in Japanese)

[9] V. Grimm, U. Berger, F. Bastiansen, S. Eliassen, V. Ginot, J. Giske et al., "A standard protocol for describing individual-based and agentbased models," *Ecological Modeling*, vol. 198, pp. 115–126, 2006.

[10] V. Grimm, U. Berger, D. DeAngelis, J.C. Polhill, J. Giske, S.F. Railsback, "The ODD protocol: A review and first update," *Ecological Modeling*, vol. 221, pp. 2760-2768, 2010.

[11] T. Nagaoka, J. Sawada, and K. Hirata, "Did the Jomon people have a short lifespan? Evidence from adult age-at-death estimation based on the auricular surface of the ilium," *Anthropological Science*, vol. 116, pp. 161-169, 2008.

[12] T. Kivisild, H.-V. Tolk, J. Parik, Y. Wang, S.S. Papiha, H.-J. Bandlt, and R. Villems, "The emerging limbs and twigs of the East Asia mtDNA tree," *Molecular Biology and Evolution*, vol. 19, pp. 1737-1751, 2002.

[13] Q.-P. Kong, Y.-G. Yao, C. Sun, H.-J. Bandelt, C.-L. Zhun, and Y.-P. Zhang, "Phylogeny of East Asian mitochondrial DNA lineages inferred from complete sequence," *American Journal of Human Genetics*, vol. 73, pp.671-676, 2003.

[14] S. Koyama, Jomon zidai, Chuo Korin Sha, 1984. (in Japanese)

[15] J.S. Dean, G.J. Gumerman, J.M. Epstein, R.L. Axtell, A.C. Swedlund, M.T. Parker, and S. McCarroll, "Understanding Anasazi Culture Change Through Agent-Based Modeling," *Dynamics in Human and Primate Societies*, Edited by T.A. Kohler, and G.J. Gumerman, pp. 179-205, 2000.