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Farmland Consolidation by Plot Exchange: A Simulation-based Approach

Yutaka Arimoto[1], Shinsaku Nakajima[2]* and Kohji Tomita[3]

This paper quantitatively examines by simulation the extent to which plot exchange can consolidate fragmented farmland. We first show that individual, decentralized, one-to-one plot exchanges, which are currently conducted by some leading farmers, cannot accomplish sufficient consolidation. This is because occurrences of "double-coincidence-of-wants" necessary for voluntary exchange are too few. We then propose a collective, centralized approach, based on the top trading cycle algorithm by Shapley et al., in which many farmers simultaneously exchange plots. This approach mitigates the restriction of "double-coincidence-of-wants" and can raise the consolidation rate to more than twice that of the individual-decentralized exchange. We also find that the consolidation rate improves dramatically as more farmers participate in the exchange. Our results suggest that it is essential to attract as many farmers as possible and to conduct collective and centralized allocation of plots in order to attain better consolidation.

Key words: farmland consolidation, *Kokan Bungo* (land exchange and consolidation), top trading cycle algorithm

1. Introduction

A major characteristic of Japanese agricultural landownership is that farmers own small, fragmented land plots. Owning of fragmented land impedes use of machinery and inhibits efficient production (Kawasaki, 2010). To improve productivity and maintain or enhance agricultural production capacity, consolidating fragmented plots is necessary.[1)]

While fragmented farmland ownership impedes efficient production, why has consolidation of farmland plots through such means as spontaneous exchange of plots not progressed as intended? This paper presents answers to this question regarding "double coincidence of wants." Assume a farmer who owns the consolidated plots consisting of several connected plots (main plot) and a distant plot intends to implement land consolidation (connection) by exchanging the distant plot with a plot next to the main plot. Here, the farmer can only negotiate with farmers owning a plot next to the main plot, as it is impossible to move farmland (locational immovability) (Shogenji, 1998). Moreover, to realize a spontaneous exchange of plots, there must be a situation in which the other farmer also wants his plot, thus satisfying the "double coincidence of wants." It is extremely rare to find such an exchange partner from among the naturally small number of candidates. This indicates that it is very difficult for individual farm-

[1] Institute of Economic Research, Hitotsubashi University
arimotoy@ier.hit.u.ac.jp
[2] Meiji University
Corresponding author*: anakajim@meiji.ac.jp
[3] National Institute of Advanced Industrial Science and Technology
k.tomita@aist.go.jp

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These authors contributed equally to this work. Author names are listed alphabetically.

ers to reach an agreement with other farmers on land exchange on a one-to-one basis.[2)] If this is the case, more fundamental measures of political intervention, such as "*Kanchi*" (land replotting) and "*Kokan Bungo*" (land exchange and consolidation), may be necessary.

The purpose of this paper is to quantitatively present to which degree consolidation of farmland[3)] through spontaneous plot exchange is possible based on simulations, and propose a more efficient method of farmland consolidation. We first discuss farmland consolidation through plot exchange in a framework of the "exchange of indivisible goods" under matching theory, thereby positioning it as an issue of resource allocation. Based on this framework, we conduct a simulation assuming a lowland, mainly rice-farming, village in a prefecture other than Hokkaido. To reproduce what is actually going on in a laissez-faire farming village, we discuss the cases of individual, decentralized exchange in which individual farmers negotiate on plot exchange on a one-to-one basis. We then show how rare the cases in which the double coincidence of wants occurs, making the progress of farmland consolidation difficult.

After presenting these negative results above, this paper proposes a more efficient method of farmland consolidation. It is a method of collective, centralized exchange based on the Top Trading Cycle (TTC) algorithm by Shapley *et al.* (1974), where many farmers inform their plots that they desire to exchange with others to a mediator and the mediator redistributes the gathered plots at one time. This method may make exchange possible by forming a cycle of exchange even when the double coincidence of wants is not directly satisfied, and we show that a consolidation rate more than double the performance of the individual, decentralized exchange can be achieved. These results mean that more efficient allocation can be realized by setting opportunities for collective, centralized exchanges.

Contributions of this paper are as follows. First is to add insights into the possibility of farmland consolidation through individual plot exchange. Today, spontaneous, individual plot exchange or farming exchange is conducted among some large-scale farm operators (Hosoyama, 2004, 2011; Ando, 2013). In Hokkaido in particular, spontaneous, individual plot/farming exchanges between farmers have been widely seen for a long time. This paper quantitatively shows that there is a limit to farmland consolidation through this method of exchange.

Second is to propose a specific method to raise the rate of farmland consolidation. Today, consolidation of farmland is conducted either by "*Kanchi*," which is collective redistribution of farmland associated with land improvement projects to change the locations or shapes of plots, or by "*Kokan Bungo*,"[4)] which is collective exchange of existing plots not associated with land improvement projects. However, organizational resource allocation associated with collective decision-making, such as *Kanchi* and *Kokan Bungo*, is likely to generate conflicts of interest, making consensus-building difficult (Ishida *et al*., 1990; Nohmi, 1995; Nakajima *et al*., 2011; Fukuyo, 2002). It is therefore necessary to design and propose a new, more desirable system that can facilitate smooth implementation of *Kanchi* or *Kokan Bungo*. Regarding the method to determine the plot to be allocated through land replotting, Cay *et al.* (2010) compared a personal interview-based method and a mechanical method of designating a plot in the area in which the largest existing plot is located, and showed that the latter could achieve better performance in terms of the number of the consolidated plots. Tanaka (2007) reports the results of a laboratory experiment of consolidating fragmented farmland plots through direct negotiations or auctions. This paper proposes a method of simultaneous exchange employing the TTC algo-

1) For more details of the research trends on farmland concentration, see Arimoto *et al.* (2013).

2) It is similarly true for goods other than farmland that the double coincidence of wants makes trading difficult. Generally, this friction is eliminated by money mediating transactions (Kiyotaki *et al*., 1993).

3) Besides through exchange, consolidation of farmland may be implemented through transfer of ownership or the right to use. Farmland consolidation through transfer, however, is associated with decision-making of the transferrer regarding farm retirement or change in the management area, which involve issues irrelevant to farmland transactions. We therefore decided to focus on consolidation through exchange, which is free from these issues, in this paper.

4) For differences between *Kanchi* and *Kokan Bungo*, see Morita (1993) and Shimamoto (1992).

rithm, and also presents a simulation-based guide for determining the details of the algorithm.

The structure of the following sections is as follows. Section 2 explains the issue of farmland consolidation through plot exchange. Section 3 describes the algorithm of exchange employed for the simulation, and Section 4 presents the settings for the simulation. Section 5 reports the results of the simulation; after presenting the probability of finding an exchange partner, it shows to which degree plot consolidation can be achieved through exchange in different scenarios and algorithms. Finally, Section 6 provides summary and conclusion.

2. Problem of Farmland Consolidation through Plot Exchange

Imagine a farming village consisting of several farming households. Each farmer owns fragmented farmland plots[5] within the village. For simplicity, we assume that all farmland plots with equal areas in the village are indifferent in quality, and that the farmers are non-discriminatory about all the plots. A group of plots contacting (connected with) others on their sides[6] is called the consolidated plots, in which continuous machine operations are available. The consolidated plots in which the plots before exchange are most densely located, in other words, the consolidated plots with the largest area,[7] is called the "main plot." Figure 1 shows an example of four farmers, who each own their main plot in one of the four corners. The plots constituting the main plot of farmer i are collectively represented with M_i, while the plots outside the main plots are called "outlying plots (isolated plots)." Some outlying plots may be

	A	B	C	D	E	F	G	H
1	1	1	2		1	2	4	4
2	1	1	2				4	4
3	3	4	2				1	3
4								
5					1			
6		3	1				1	
7	2	2				4	3	3
8	2	2					3	3

Figure 1. Schematic diagram of fragmented farmland

Note: Cell shows the plot, the cell number shows the number of the farmer who possesses the plot.

connected, forming the consolidated plots (not the main plots). Among the outlying plots, the plots that can be exchanged with others without causing a division of the consolidated plots are called "exchangeable outlying plots" and are represented with z_i each, and with Z_i collectively. And this condition is called the "indivisibility requirement." In Figure 1, Farmer 2 has the consolidated plots of outlying plots of {C1, C2, C3}. If plot C2 is exchanged with other plot, this consolidated plots will be divided. Therefore, Z_2 = {C1, C3}.

The purpose of farmland consolidation for farmers is to consolidate fragmented plots through exchanges, thereby reducing the number of the consolidated plots. This paper considers three constraints in this process: 1) The main plots should be maintained unmoved.[8] 2) Unexchangeable outlying plots should not be moved, so as to minimize relocation of plots unless it contributes to consolidation. 3) The number of the consolidated plots should not be increased.

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5) The essence of this problem will not be affected if the farmland is leased.

6) The institutional definition of the consolidated plots may include a group of plots contacting others at points (National Chamber of Agriculture, 2009: p.18). If accepting the cases of contacting on points, however, the consolidated plots consisting of broadly scattered plots though contacting with others on points may be formed. Thus, we decided to intuitively require contacting on sides.

7) In the simulation, the main farm is randomly chosen when there are several consolidated plots with the same area.

8) Compared to any other plot which objectively seems equivalent, farmers tend to have a strong attachment to their existing land, seeing it as their family property they have inherited from their ancestors in which they have long invested a lot of resources for improving soil and providing care. Taking into consideration such subjective preference of farmers and respecting their realistic desire to continue to own their existing land, this paper discusses the case of consolidating farmland plots into the main plots. In actual processes of *Kanchi*, "*Bochi-Shudanka-Hoshiki*" (the main plots-based consolidation method) or "*Misshuchi-Shudanka-Hoshiki*" (the dense plots-based consolidation method), which consolidates plots around the area in which the plots are most densely located before exchange, is generally employed.

For the purpose and under the constraints above, each farmer can be assumed to prefer plots adjacent to their main plots to outlying plots. Thus, the farmer requests or accepts exchange of z_i only when it can be exchanged with a plot adjacent to its main plots.[9] We call the farmer requesting exchange the "offerer" and the farmer accepting the exchange the "accepter." The plots adjacent to farmer i's main plots M_i are collectively represented with M_i'. As farmer i accepts exchange with an exchangeable outlying plot z_i as long as it is within the range of M_i', we call this an "acceptable domain." Other farmers owning exchangeable outlying plots in M_i' are represented with j, and collectively with μ_i. In the case of Farmer 1 in Figure 1, $M_1' = \{A3, B3, C1, C2\}$, and $\mu_1 = \{2, 3, 4\}$.

Offerer i proposes to accepter $j \in \mu_i$ an exchange of its z_i with z_j of the accepter j. Here, z_j is adjacent to the main plots of offerer i, and thus satisfies:

$$z_j \in M_i' \quad (1)$$

Accepter j accepts the exchange only when:

$$z_i \in M_j' \quad (2)$$

In other words, the accepter accepts the exchange only when z_i of offerer z_i is a plot adjacent to its own main plots and the exchange can turn its exchangeable outlying plot z_j into a plot next to the main plots, as in the case for the offerer. When the above (1) and (2) are both satisfied, such a situation is called the "double coincidence of wants." When there is a double coincidence of wants, $j \in \mu_i$ and $i \in \mu_j$ are both satisfied. In the case of Figure 1, $\mu_1 = \{2, 3, 4\}$, $\mu_2 = \{3\}$, $\mu_3 = \{1, 4\}$, $\mu_4 = \{1, 2, 3\}$, where, direct exchanges of $1 \leftrightarrow 3$, $1 \leftrightarrow 4$, and $3 \leftrightarrow 4$ are possible.

The issue of farmland consolidation through plot exchange may be considered as a kind of "problem of indivisible goods exchange." The problem of indivisible goods exchange means the task of "redistributing goods whose division is inappropriate or impossible while paying attention to initial ownership" (Sakai *et al.*, 2008: p. 137). A well-known typical example of this is the "housing market problem," where students allocated with rooms in a dormitory reallocate the rooms in a more desirable way according to each student's preference, and several theoretical studies have been conducted on this problem.[10] The housing market problem in general, however, differs from the problem of farmland consolidation in three points. First, while the housing market problem involves analysis of cases in which only a unit of indivisible goods is consumed, the farmland consolidation problem deals with several units of goods (plots). Second, in farmland consolidation, connection between plots is significant and therefore there is complementarity (externality) between goods[11]. Third, in farmland consolidation, the plots adjacent to the main plots vary as the main plots expand due to exchange, causing dynamic changes in farmers' preferences regarding plots.

3. Algorithms of Plot Exchange

This section presents two algorithms for simulation of farmland consolidation through plot exchange. The first is for the purpose of reproducing a situation which is likely to be seen in an actual farming village, where each farmer desiring land consolidation proposes an exchange directly to other farmers on a decentralized, one-to-one basis. The second, for the purpose of proposing a method that can maximize the effects of consolidation and verifying the effects, represents a case in which farmers desiring consolidation bring the plots they are willing to exchange with others to a mediator such as an agricultural cooperative, and the mediator redistributes the plots at one time.

1) Direct exchange method

We call the cases in which each farmer proposes an exchange directly to other farmers on a decentralized, one-to-one basis the "direct exchange method." An outline of the algorithm of this method is as follows:

1. Randomly determine the order of farmers (offerer) to propose an exchange (explained below).

9) The purpose of limiting the plots subject to exchange to exchangeable outlying plots is to eliminate the possibility that exchange with an outlying plot not satisfying the indivisibility requirement may cause division of the consolidated plots, resulting in an increase in the number of the consolidated plots.

10) For explanation in "housing market problem," see Sakai *et al.* (2008) and Sakai (2010).

11) As studies addressing these points, Konishi *et al.* (2001: Section 5) discusses cases of several units of goods and Shapley *et al.* (1974: Section 8) discusses cases of several units of goods with complementarity.

2. Select the offerer i according to the order determined in Step 1 above.
3. For each farmer k, identify/update main plots M_k, acceptable domain M_k', collection of exchangeable outlying plots Z_k, and collection μ_k of accepters j who own plots within M_k'.
4. Offerer i decides the priority order for combination of plots to be exchanged (z_i, a_j), $z_i \in Z_i$, $a_j \in M_i'$, according to the specified rules (explained later).
5. Offerer i proposes an exchange to the owner j of the plot a_j of the combination z_i, a_j at the top of the list of Step 4. As accepter j accepts the exchange if $z_i \in M_j'$, exchange z_i with a_j, and return to Step 3. If accepter j refuses the exchange, offerer proposes an exchange of the plots of the next combination in the list. If no farmer accepts the exchange, go back to Step 2 and select the next farmer of the offerer list.
6. Even when Steps 2 through 5 have been completed for all farmers, another exchangeable plots may arise in the processes. Therefore, repeat the processes in cycles until no exchangeable plots remain, and then finish the procedure.

Among these processes, Steps 1, 3 and 4 may have several variations. So, we try the variations summarized in Table 1 in the simulation. There are three key points with regard to the variations.

First is the order of offerers (Step 1). In reality, larger-scale farmers are presumed to have a stronger incentive for farmland consolidation. We therefore simulate a case in which farmers are approached for exchange in order from the largest-scale farmer to the smallest. For comparison, we also simulate the order starting from the smallest-scale farmer.

Second is the definition of exchangeable plots (Step 3). We first try a method of exchanging only exchangeable outlying plots. We then implement a method that allows exchange of the expanded plots that have undergone an exchange and are consequently connected to the main plots (called "expanded main plots"). While the former is associated with the benefit of enabling the farmer to turn outlying plots into plots connected to the main plots, the latter generates no specific benefits for the farmer as it only changes the shape of the main plots and

Table 1. Algorithm combinations

	Individual, direct exchange method			Trading cycle method		
	Exchangeable plot	Offerer order	Accepter, Outlying plot	Exchangeable plot	Cycle	Priority order
1	Exchangeable outlying plot	Offerer: large	Accepter: large	Exchangeable outlying plot	Cycle: short	Large scale
2	Exchangeable outlying plot	Offerer: large	Accepter: small	Exchangeable outlying plot	Cycle: short	Small scale
3	Exchangeable outlying plot	Offerer: large	Outlying plot: farther	Exchangeable outlying plot	Cycle: long	Large scale
4	Exchangeable outlying plot	Offerer: large	Outlying plot: close	Exchangeable outlying plot	Cycle: long	Small scale
5	Exchangeable outlying plot	Offerer: small	Accepter: large	Exchangeable outlying plot + Expanded main plots	Cycle: short	Large scale
6	Exchangeable outlying plot	Offerer: small	Accepter: small	Exchangeable outlying plot + Expanded main plots	Cycle: short	Small scale
7	Exchangeable outlying plot	Offerer: small	Outlying plot: farther	Exchangeable outlying plot + Expanded main plots	Cycle: long	Large scale
8	Exchangeable outlying plot	Offerer: small	Outlying plot: close	Exchangeable outlying plot + Expanded main plots	Cycle: long	Small scale
9	Exchangeable outlying plot + Expanded main plots	Offerer: large	Accepter: large			
10	Exchangeable outlying plot + Expanded main plots	Offerer: large	Accepter: small			
11	Exchangeable outlying plot + Expanded main plots	Offerer: large	Outlying plot: farther			
12	Exchangeable outlying plot + Expanded main plots	Offerer: large	Outlying plot: close			
13	Exchangeable outlying plot + Expanded main plots	Offerer: small	Accepter: large			
14	Exchangeable outlying plot + Expanded main plots	Offerer: small	Accepter: small			
15	Exchangeable outlying plot + Expanded main plots	Offerer: small	Outlying plot: farther			
16	Exchangeable outlying plot + Expanded main plots	Offerer: small	Outlying plot: close			

cannot connect outlying plots to it. The latter, however, plays a charitable role; by offering the expanded main plots, it helps other farmers consolidate their farmland plots.[12)]

Third is how to determine which plots should be exchanged with whom (Step 4). For this issue, we discuss two approaches; one is deciding the (offerer's) plots of outlying plots to be subject to exchange first and the other is deciding the exchange partner (accepter) first. For the former, we try both the order from the farthest outlying plot to the closest one, and the order from the outlying plot constituting the smallest consolidated plots to the largest one. Starting from farther plots may help shorten the distance between the farmer's house and the farmland. Starting with consolidating the outlying plot constituting the smallest consolidated plots, on the other hand, may minimize the number of the consolidated plots and help achieve a higher consolidation rate. These methods, however, require negotiation with a different farmer for each plot, though in reality once the offerer starts negotiation with a farmer, he will continue to negotiate on all the plots owned by the same farmer. So, we try a variation of placing priority on selecting the accepter, instead of the plots. While which farmer should be approached first may be influenced by the closeness of personal relationship, etc., we try in the simulation both the descending and ascending orders in terms of the management scale of the accepter.[13)]

2) Trading cycle method

The problem of the direct exchange method is that it requires satisfaction of the double coincidence of wants between the offerer and the accepter and therefore the trading opportunities are extremely limited. In the case of Figure 1, for example, Farmer 2 cannot establish the double coincidence of wants with any other farmers and therefore cannot exchange plots. However, if three or more farmers collectively participate in the exchange at the same time, plot exchange may become available. As the specific procedure for this, the idea used in the Top Trading Cycle (TTC) algorithm (Shapley *et al.*, 1974) for the problem of indivisible goods exchange can be applied. Farmers form a cycle in which each farmer points at the other farmer who owns the plot he wants most, and exchange plots within the cycle. In the case of Figure 1, Farmer 2 wants Farmer 3's plot B6, Farmer 3 wants Farmer 4's plot F7, and Farmer 4 wants Farmer 2's plot F1. These relationships are described as a cycle of 2 → 3 → 4 → 2. In this cycle, Farmer 2 and Farmer 3 first exchange F1 and B6, and then Farmer 3 and Farmer 4 exchange F1 and F7. In this way, all parties can obtain the plots they want (Figure 2). Generally, exchange is possible if a cycle can be formed by describing each plot owner pointing at the owner of the plot he wants. In the case of Figure 2, nine cycles can be formed as shown in Figure 3. The key point is that the number of exchangeable plots can be increased by participation of multiple farmers bringing their plots, and the requirement of double coincidence of wants can be eased because multiple farmers join the exchange at the same time.

To demonstrate the advantage of this method, we discuss a situation in which farmers declare to a mediator such as an agricultural cooperative the outlying plots they wish to exchange with other plots, to combine with their main plots to form the consolidated plots, and the me-

12) In the variation of allowing exchange of the expanded main plots, the offerer is assumed to be always willing to put their outlying plots up for exchange. In the variation of placing priority on selecting the accepter, after deciding the accepter regardless of whether the accepter's exchangeable plots are of outlying plots or expanded main plots, we try exchange of outlying plots first, and only when there are no exchangeable outlying plots, we put the expanded main plots up for exchange.

13) The priority orders are determined lexicographically as follows: In the approach of deciding the offerer's plots of outlying plots to be subject to exchange first, 1) when according to the order from the farthest outlying plot to the closest one, if the distance is the same, we select the one constituting the smallest consolidated plots, and 2) when according to the order starting from the smallest outlying plot, if the size is the same, we select the farther plot. Then if there are several prospective accepters with whom these selected outlying plots are exchangeable, we select the smaller-scale accepter. The accepter's plots to be subject to exchange are decided according to the rules similar to those for selecting the offerer's plots (farthest outlying plot > smallest outlying plot, or smallest outlying plot > farthest outlying plot). In the approach of deciding the accepter first, we determine the accepter based on scale. If the selected accepter has several exchangeable plots, we select the smaller plots (if the size is the same, the farther plots) for both the offerer and the accepter.

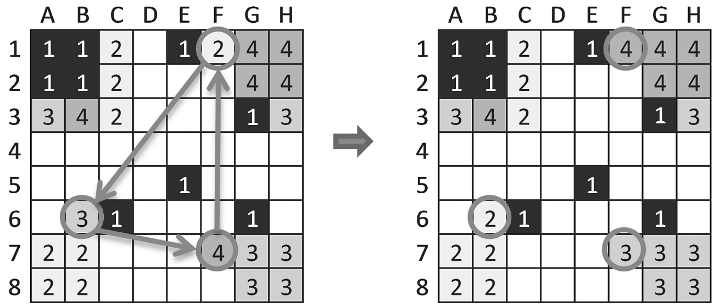


Figure 2. Example of trading cycle method (2 → 3 → 4 → 2)

1 → 2 → 3 → 1	1 → 3 → 4 → 1	1 → 4 → 3 → 1
1 → 2 → 3 → 4 → 1	1 → 4 → 1	2 → 3 → 4 → 2
1 → 3 → 1	1 → 4 → 2 → 3 → 1	3 → 4 → 3

Figure 3. Exchangeable cycle

diator re-allocates the gathered outlying plots to the new owners. Allocation here means allocating a new owner to each of the plots held by the farmers. In comparison with the direct exchange method, in which individual farmers exchange their plots on a decentralized, one-to-one basis, multiple farmers collectively participate in centralized allocation by a mediator.

The next task is to determine what kind of allocation should be conducted, and in what way (algorithm). A desirable method of allocation should at least satisfy individual rationality (all participants can acquire plots that are equivalent to or better than those before reallocation) and efficiency (the allocation requires no Pareto improvement). In the housing market problem, where each individual exchanges a single indivisible good with others, there uniquely exists a strong core allocation that has robustness against deviation by coalition[14] besides individual rationality and efficiency, and this allocation is enabled by the TTC algorithm. Meanwhile, in the case of the farmland consolidation problem, in which farmers consume several units of indivisible goods, the existence of a core is not always guaranteed (Shapley *et al.*, 1974: Section 8; Konishi *et al.*, 2001: Section 5). Moreover, in the farmland consolidation problem, it is assumed that there is complementarity between goods (through connection), farmers' preference regarding plots dynamically changes, and the plots adjacent to the main plots are equally preferable. This means there are several plots for which farmers' preferences are indifferent, making the problem complicated. As far as I know, no algorithm has been found to solve such a problem.

Thus, this paper discusses a sequential algorithm based on the idea of cycle formation in the TTC algorithm. It is a repeated sequence of creating a cycle in which each farmer participates with one of the plots they have submitted and redistributing the plots within the cycle.[15] We call this algorithm the trading cycle method. An outline of the algorithm is as follows:

1. For each farmer k, identify/update main plots M_k, acceptable domain M'_k, collection of exchangeable outlying plots Z_k, and collection μ_k of accepters j who own plots within M'_k.
2. Make a list of cycles regarding μ_k. Specifically, according to the TTC algorithm, have each farmer point at all the accepters who own the plots that the farmer wants to exchange with, and create cycles.
3. From among the listed cycles, choose one

14) A strong core allocation also satisfies strategy-proofness.

15) To maximize the farmland consolidation rate of a village, distributing all the submitted exchangeable plots at one time is more desirable than following this sequential algorithm. Because it was difficult to find such an algorithm that enables optimal distribution, this sequential algorithm was adopted as the second-best approach to conduct the simulation.

in accordance with the specified rules (explained later). Have each of the farmers belonging to the selected cycle submit the outlying plot to the farmer pointing at him and receive his plot instead. Then go back to Step 1.

4. Repeat the processes until no exchangeable cycles remain, and then finish the procedure.

In an actual situation, there is no need for each farmer to point at others. Instead, cycles can be created mechanically by the mediator if the outlying plots for exchange and the main plots for consolidation are declared in advance.

In the simulation, we try several variations for Steps 1 and 3. There are two key points. First is the definition of exchangeable plots (Step 1). As in the case of the direct exchange method, we simulate two variations: one accepting only exchangeable outlying plots and the other accepting both exchangeable outlying plots and the expanded main plots. The second point is how to select the cycles (Step 3). We have decided to select based on the length of each cycle and the scale of farmers involved in the cycle. In other words, we first choose the longest (or shortest) cycles, and then, if there is more than one such cycle, choose the cycle involving the largest-scale (or smallest-scale) farmer. In the case of Figure 1, for example, the following cycles are selected.[16)]

When priority is placed on:
Shortest cycle × smallest scale: 1→3→1
Shortest cycle × largest scale: 3→4→3
Longest cycle × smallest scale: 1→2→3→4→1
Longest cycle × largest scale: 1→4→2→3→1

Prioritizing longer cycles can help many farmers achieve farmland consolidation quickly. As for the priority order of farmers involved in a cycle, prioritizing smaller-scale farmers is likely to help achieve a high consolidation rate. This is probably because very few cycles are available for small-scale farmers to join and therefore they should complete exchanges as soon as they get involved in a cycle. Large-scale farmers, on the contrary, have a broader M_k' and many outlying plots, and can therefore easily join cycles and accomplish exchange even after small-scale farmers have completed exchanges.

4. Settings for Simulation

1) Settings

As the settings for simulation of exchange, we assume an agricultural village consisting of 30 farming households, with a total area of 30 ha, and comprising 300 plots (0.1 ha each) in total.[17)] These settings are determined based on the average per-village figures (farmland area: 31.4 ha, farming households: 29.2 households) released in the World Census of Agriculture and Forestry 2000 for flatland agricultural areas in prefectures other than Hokkaido.

For the area of each farmer, 100 patterns are randomly created from an exponential distribution with mean 1. To ensure consistency with the reality, we compared the distributions of the number of farm households (management units) by the area of arable land owned, obtained from the World Census of Agriculture and Forestry 2000 and 2010, with the created data, and confirmed that the created data was approximate to the actual distribution. After that, for each of the farmland area patterns created, we randomly set 100 patterns of farmland layout before exchange. As a result, $100 \times 100 = 10{,}000$ patterns of the area-layout combination were prepared.

Regarding farmers' participation in the exchange, we tried seven scenarios by varying the participation rate and the participation pattern (Table 2). Since not all farmers of the village are willing to exchange their plots, we set the scenarios with participation rates of 25%, 50%, 75%, and 100%. For scenarios with a participation rate of less than 100%, we set the case of uniform participation by farmers of all scales

16) In the case of prioritizing the longest cycle in this example, farmers involved in the selected cycle are the same whether the priority is placed on the largest scale or the smallest scale, because all the farmers participate in the exchange. Generally, however, even when the length is the same, different cycles involve different farmers and therefore the selected cycle varies depending on the priority in terms of the scale of the farmers involved.

17) The reason why we set an agricultural village as the range of exchange is that *Kanchi* or *Kokan Bungo* is actually often implemented for each unit (in the case of farmers who own farmland outside the village, such farmland plots are often turned into plots adjacent to the farmers' residing village and the village boundary is revised accordingly), and therefore it is appropriate to set an agricultural village as the range for plot exchange.

Table 2. Farmers'participation scenario

Participation ratio	Participation pattern	Area ranking (small ←→ large) 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
100%	Equal	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
75%	Equal	1	1	0	1	1	1	1	1	0	1	1	0	1	1	1	1	1	0	1	1	0	1	1	1	1	1	0	1	1	0
75%	Large scale	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
50%	Equal	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1
50%	Large scale	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
25%	Equal	0	0	0	1	0	0	1	0	0	0	1	0	0	1	0	0	0	1	0	0	1	0	0	0	1	0	0	1	0	0
25%	Large scale	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1

Note: This table shows that the lower the area rank is, the smaller the area of farmland is. 1 for participation, 0 for nonparticipation.

Table 3. Participation ratio × rate of farmland consolidation according to algorithm combinations (village level)

	Individual, direct exchange method																Trading cycle method							
	Exchangeable outlying plot								Exchangeable outlying plot + Expanded main plots								Exchangeable outlying plot				Exchangeable outlying plot + Expanded main plots			
	Offerer: large				Offerer: small				Offerer: large				Offerer: small				Cycle: short		Cycle: long		Cycle: short		Cycle: long	
	Accepter		Outlying plot		Accepter		Outlying plot		Accepter		Outlying plot		Accepter		Outlying plot		Priority order		Priority order		Priority order		Priority order	
	large	small	farther	close	large	small	farther	close	large	small	farther	close	large	small	farther	close	large	small	large	small	large	small	large	small
Panel A : Equal participation																								
Participation ratio: 25%	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.007	0.007	0.008	0.008	0.007	0.007	0.008	0.008
Participation ratio: 50%	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.040	0.040	0.039	0.040	0.040	0.040	0.040	0.040	0.093	0.092	0.104	0.104	0.104	0.104	0.113	0.113
Participation ratio: 75%	0.066	0.066	0.065	0.066	0.066	0.066	0.065	0.066	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.251	0.248	0.290	0.290	0.340	0.337	0.360	0.358
Participation ratio: 100%	0.276	0.277	0.273	0.275	0.277	0.279	0.275	0.278	0.390	0.391	0.386	0.388	0.391	0.390	0.386	0.388	0.624	0.632	0.716	0.716	0.967	0.961	0.965	0.955
Panel B : Large-scale overemphasis participation																								
Participation ratio: 25%	0.081	0.081	0.080	0.081	0.082	0.082	0.080	0.081	0.091	0.091	0.090	0.091	0.092	0.092	0.090	0.091	0.156	0.156	0.174	0.173	0.188	0.188	0.199	0.198
Participation ratio: 50%	0.195	0.196	0.193	0.195	0.197	0.198	0.194	0.197	0.255	0.255	0.252	0.254	0.255	0.256	0.251	0.254	0.450	0.454	0.519	0.519	0.688	0.683	0.699	0.691
Participation ratio: 75%	0.263	0.264	0.261	0.262	0.264	0.265	0.262	0.265	0.368	0.368	0.364	0.366	0.369	0.368	0.364	0.366	0.597	0.604	0.686	0.687	0.927	0.921	0.927	0.916

Note: Based on the randomly created 10,000 area×layout patterns, this table shows the average of the simulation results varying the farmers'participation scenario×algorithm patterns. The crossbar which shows the rate of farmland consolidation is adjusted between 0 and 1.

and the case of biased participation by farmers of larger scales, who are expected to be benefited greatly from land consolidation.

Variations of the algorithm are as summarized in Table 3. There are 16 variations for the direct exchange method. For each of the 10,000 patterns of the area-layout combination, 112 types (7 participation scenarios × 16 variations) of exchange are conducted, making a total of 1,120,000. The trading cycle method, on the other hand, has eight variations. For each of the area-layout combination patterns, 56 types (7 participation scenarios × 8 variations) were conducted, making a total of 560,000.

2) Evaluation of performance

Performance of farmland consolidation is measured with the consolidation rate. The consolidation rate is often used as an index to measure the performance of *Kanchi* or *Kokan Bungo*. The consolidation rate of a village is defined as:

$$y = \frac{A^0 - A^1}{A^0 - n}$$

where, A^0 and A^1 represent the total number of the consolidated plots before and after exchange, respectively, and n represents the number of farming households (set as 30 in this paper). The denominator is the maximum number of the consolidated plots that can be reduced by consolidation when one consolidated plots per household is targeted. When this value is 1, it means that the number of the consolidated plots that could be reduced have been all consolidated, and when it is 0, it means the reduction has not been achieved at all. This index can be defined also for each household, where the denominator is $A_i^0 - 1$. This definition, however, cannot be applied to a farmer with only one consolidated plots at the beginning.

5. Results

1) Number of possible exchange partners and the probability of finding them

First, we examine the degree of "double coincidence of wants" satisfied. This depends on the number of farmers with whom you want to exchange plots (the number of farmers owning plots adjacent to your main plots, hereinafter called "the number of desirable exchange partners") and the number of farmers who want to exchange plots with you (the number of farmers whose main plots is adjacent to your outlying plots, hereinafter called "the number of exchange-desiring farmers").

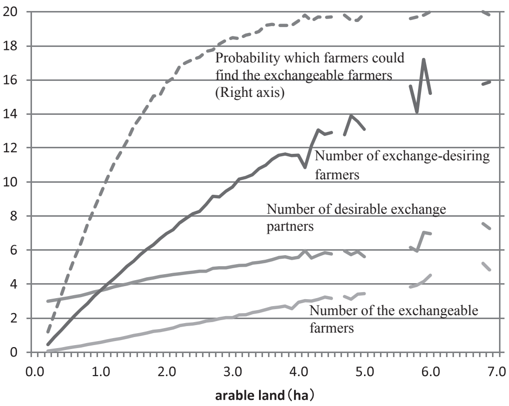


Figure 4. The number of the exchangeable farmers and its probability

Figure 4 shows the numbers of such households and the probability of finding at least one possible exchange partner in the initial state of the 10,000 area × layout patterns. The probability is the average of farmers for each management area. In the setting of this paper, farmers with 1 ha of farmland own plots in nine consolidated plots in average. Regarding the 30 farming households of the village, the number of desirable exchange partners was 3.6 and the number of exchange-desiring farmers was also 3.6 (12.6%), of which 0.6 households were able to actually exchange plots. The probability of finding at least one possible exchange partner was 46%. Thus, a farmer with 1 ha of farmland residing in an average farming village is able to exchange at least one plot with a probability of around 50%, and the probability is likely to be 80% if the farmer owns over 2 ha of farmland. This means that farmers of a certain scale are highly likely to find at least one exchange partner. To achieve consequent land consolidation, however, multiple and repeated occurrence of this matching is necessary. The following section therefore discusses the consolidation rate as the consequence of exchanges.

2) Consolidation rate by the participation ratio

Table 3 shows the consolidation rate achieved through exchange on the village level. The results of each participation scenario are presented for each algorithm variation. The figures are the average of the results of applying each of the participation scenario × variations to 10,000 patterns of area × layout combination.

First, looking at the results of the scenario in which farmers of all scales evenly participate in exchange (Table 3, Panel A), the consolidation rate is less than 1% for all variations when only 25% of the farmers of the village participate in the exchange. In other words, with participation of a quarter of the farmers of the village, successful matching that satisfies the double coincidence of wants can rarely occur. With the participation of 50%, the consolidation rate was still less than 4% for the direct exchange method and 9 to 11% for the trading cycle method. When the participation rate is 100%, however, higher participation rates of 27 to 39% for the direct exchange method and of 62 to 97% for the trading cycle method are achieved. Looking at the results of the scenario of biased participation by mostly large-scale farmers (Table 3, Panel B), on the other hand, we confirm that better performance is achieved when many large-scale farmers participate in exchange even if the total participation rate is the same.

These results indicate that the key for better performance is to gather as many participants as possible, and also to obtain the participation of larger-scale farmers if the number of participants is the same. This reflects that the higher the number of plots available for exchange, the easier it becomes to satisfy the double coincidence of wants.

3) Effects of variations

For several algorithm variations tried in the simulation, we quantitatively verified the effects of each variation on the consolidation rate by employing regression analysis. The regression equation is:

$$y_{lpv} = \alpha + \beta \text{Participation}_p + \gamma \text{Variation}_v + \delta \text{Block}_l + \sigma \text{Gini}_l + \varepsilon_{lpv}$$

where, the subscripts l, p, and v represent the area×layout pattern, the participation scenario, and the algorithm variation, respectively. The explained variable y_{lpv} is the consolidation rate. The explanatory variable of "Participation" is a group of dummy variables representing the participation scenario, for which dummy variables of the participation rate and the participation pattern, as well as the cross terms thereof, are placed in our assumption. "Variation" is a group of dummy variables representing the algorithm variation and the cross terms thereof. Moreover, to observe how dispersion of the plots before exchange and distribution (bias) of areas owned by farmers affect the results, the total number of the consolidated plots (Block) and the Gini coefficient of the area owned (Gini) are added to explanatory variables. We simulate exchanges in different variations for each of the area×layout patterns before exchange. It should be noted that since the explained variable is the ratio of consolidation to the number of the consolidated plots before exchange, results are compared between variations with a fixed area×layout combination pattern.

Major conclusions from the regression results presented in Table 4 can be summarized as follows: In both methods, the algorithm variation that allows exchange of the expanded main plots contributed most to improving the consolidation rate; with the main effect of an increase in the consolidation rate by 4.2 points for the direct exchange method and 14.4 points for the trading cycle method. This is because the number of exchangeable plots increased by including the expanded main plots in the exchange target. In the trading cycle method, an additional increase of 4.4 points was obtained in the main effect when longer cycles were selected. This is because prioritizing longer cycles enabled faster consolidation of a larger number of farmland plots. Effects of all the other variations remained less than 1 point in terms of both the main effect and the cross effect. This means that there is no need to pay much attention to the details of algorithms except for allowing exchange of the expanded main plots and prioritizing longer cycles in the trading cycle method. In the direct exchange method, for example, it is not important to consolidate smaller outlying plots (their consolidated plots) first. If completing all the exchanges with each partner, the results will not be much different.

As to the initial state, the larger the number of the consolidated plots is (or the more fragmented the consolidated plots are), the lower the rate of consolidation becomes. For example, one more consolidated plots per household (meaning 30 more consolidated plots in total) results in a decline of the consolidation rate by 1.4 points. On the other hand, consolidation becomes easier when distribution of the farmland area is biased. This is because if one large-scale farmer owns many plots, participation of this farmer in exchange can boost the number of exchangeable plots.

4) Results on the level of farmers

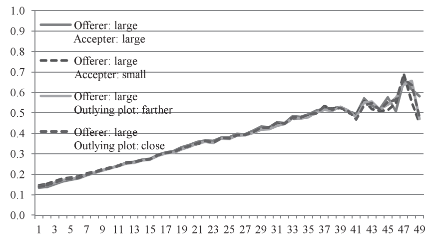
The results relevant to farmers are summa-

Table 4. Determinant factor of the rate of farmland consolidation (OLS estimation)

Individual, direct exchange method		Trading cycle method	
Participation ratio		Participation ratio	
(Reference category) Participation ratio: 25%		(Reference category) Participation ratio: 25%	
Participation ratio: 50%	0.0341***	Participation ratio: 50%	0.0960***
	(0.000572)		(0.000598)
Participation ratio: 70%	0.0634***	Participation ratio: 70%	0.302***
	(0.000662)		(0.00106)
Participation ratio: 100%	0.328***	Participation ratio: 100%	0.809***
	(0.00118)		(0.000643)
Participation pattern		Participation pattern	
(Reference category) Equal participation		(Reference category) Equal participation	
Large-scale overemphasis	0.0811***	Large-scale overemphasis	0.172***
	(0.000700)		(0.000981)
Participation ratio: 50%×Large-scale overemphasis	0.105***	Participation ratio: 50%×Large-scale overemphasis	0.313***
	(0.00130)		(0.00154)
Participation ratio: 75%×Large-scale overemphasis	0.166***	Participation ratio: 75%×Large-scale overemphasis	0.302***
	(0.00142)		(0.00157)
Exchange of Expanded main plots		Exchange of Expanded main plots	
(Reference category) Not-exchangeable		(Reference category) Not-exchangeable	
Exchangeable	0.0420***	Exchangeable	0.144***
	(0.000290)		(0.000567)
Offerer (Reference category) Offerer: small		Cycle (Reference category) Cycle: short	
Offerer: large	−0.000695***	Cycle: long	0.0435***
	(0.000163)		(0.000279)
		Priority order	
Others (Reference category) Accepter: large		(Reference category) Small-scale order	
Accepter: small	0.000451***	Large-scale order	−0.00207***
	(0.000122)		(0.000230)
Outlying plot: farther	−0.00132***		
	(0.000119)		
Outlying plot: close	8.58e−05		
	(0.000100)		
Cross term		Cross term	
Exchangeable×Offerer: large	0.000223	Exchangeable×Cycle: long	−0.0381***
	(0.000234)		(0.000317)
Exchangeable×Accepter: small	−0.000568***	Exchangeable×Large-scale order	0.00511***
	(0.000196)		(0.000277)
Exchangeable×Outlying plot: farther	−0.00114***	Cycle: long×Large-scale order	0.00207***
	(0.000208)		(0.000297)
Exchangeable×Outlying plot: close	−0.00104***	Exchangeable×Cycle: long×Large-scale order	−0.000512
	(0.000198)		(0.000361)
Offerer: large×Accepter: small	8.78e−05		
	(0.000184)		
Offerer: large×Outlying plot: farther	6.68e−05		
	(0.000168)		
Offerer: large×Outlying plot: close	−0.000355**		
	(0.000155)		
Exchangeable×Offerer: large×Accepter: small	0.000186		
	(0.000283)		
Exchangeable×Offerer: large×Outlying plot: farther	0.000541*		
	(0.000292)		
Exchangeable×Offerer: large×Outlying plot: close	0.000567**		
	(0.000282)		
Number of the initial farmland consolidation	−0.000473***	Number of the initial farmland consolidation	0.000437***
	(5.34e−05)		(5.22e−05)
Gini coefficient	0.709***	Gini coefficient	0.374***
	(0.00865)		(0.00852)
Constant term	−0.208***	Constant term	−0.363***
	(0.0165)		(0.0162)
Sample size	1,120,000	Sample size	560,000
Adjusted R^2	0.672	Adjusted R^2	0.896

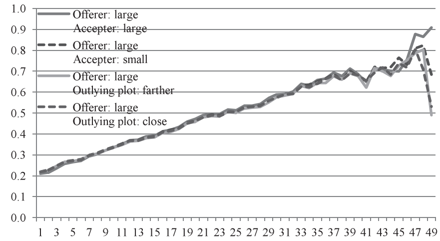
Note: ***, ** and * indicate significance levels of 1%, 5% and 10%, respectively.

Figures in parentheses show cluster-robust standard error.



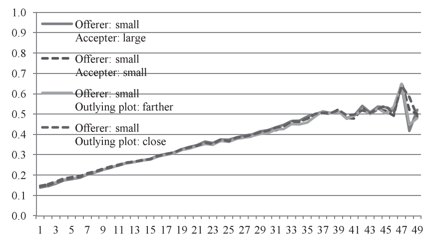
Individual, direct exchange method:

Offerer: large



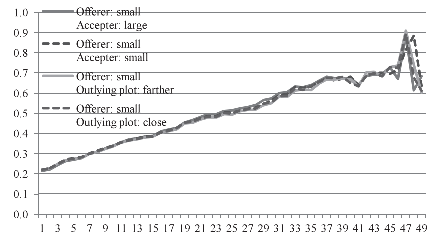
Individual, direct exchange method:

Offerer: large



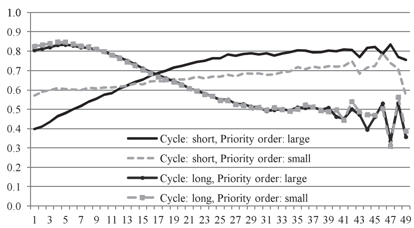
Individual, direct exchange method:

Offerer: small



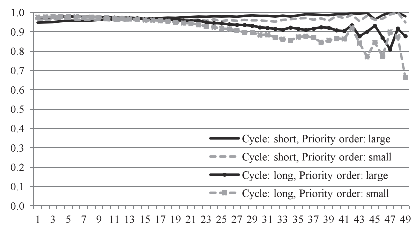
Individual, direct exchange method:

Offerer: small



Trading cycle method

Exchangable plot: Exchangeable outlying plot



Trading cycle method

Exchangable plot: Exchangeable outlying plot＋Expanded main plots

Figure 5. The rate of farmland consolidation according to the reduction possible farmland consolidation plots

Note: Horizontal axis shows the number of the consolidated plots that can be reduced (λ).

rized as follows. Particular attention is paid to whether the scale of farmers affects the consolidation rate, as it may determine the farmers' incentive to participate in exchange. A method that enables uniform consolidation regardless of the size of farmers may attract many participants. Or it may be a good idea to employ an algorithm that can achieve a particularly high consolidation rate for large-scale farmers, thereby encouraging their participation. Here, as an index to reflect the scale of farmers, we use "the number of the consolidated plots that can be reduced" defined with "the number of existing consolidated plots -1," described as λ. λ is the maximum number of the consolidated plots that can be reduced through consolidation and

Table 5. Standard errors of farmers' rate of farmland consolidation according to algorithm combinations
(Participation ratio: 100%)

	Individual, direct exchange method								Trading cycle method			
	Offerer: large				Offerer: small				Cycle: short		Cycle: long	
	Accepter		Outlying plot		Accepter		Outlying plot		Priority order		Priority order	
	large	small	farther	close	large	small	farther	close	large	small	large	small
Exchangeable outlying plot	0.244	0.247	0.245	0.245	0.246	0.248	0.246	0.247	0.348	0.324	0.245	0.242
Exchangeable outlying plot +Expanded main plots	0.295	0.297	0.295	0.296	0.297	0.297	0.296	0.297	0.145	0.132	0.105	0.108

serves as the denominator of the consolidation rate on the farmer level.

Figure 5 shows the average consolidation rate for farmers according to the number of the consolidated plots that can be reduced (λ). These are the results of the 100% participation scenario. In the direct exchange method, the consolidation rate rises almost linearly in proportion to λ. (The results for large-scale farmers with λ of 37 or over are unstable because samples are too few.) This tendency is the same for all variations. Therefore, we can conclude that in the direct exchange method, large-scale farmers with many fragmented plots are likely to be greatly benefited from consolidation through exchange.

Meanwhile, in the trading cycle method, different results are obtained depending on whether exchange of the expanded main plots is allowed, and the length of the cycle. First, when exchange of the expanded main land plots is allowed, a high consolidation rate of over 90% can be achieved regardless of the value of λ. When exchange of the expanded main plots is not allowed, results vary depending on the type of the cycle selected. A short cycle is advantageous to the large-scale farmers while a long cycle is advantageous to small-scale farmers. This tendency is similarly seen in the case of allowing exchange of the expanded main plots.

Finally, for each variation, standard errors of the consolidation rate are calculated (Table 5). In the direct exchange method not allowing exchange of the expanded main plots, the standard error is between 0.24 and 0.25 regardless of the variation. When exchange of the expanded main plots is allowed, the standard error is slightly higher, 0.297. In the trading cycle method, when exchange of the expanded main plots is not allowed, the standard error varies widely, between 0.324 and 0.348 for short cycles and between 0.242 and 0.245 for long cycles. When exchange of the expanded main plots is allowed, on the contrary, a high consolidation rate can be achieved regardless of the scale, resulting in small variation in the standard error. (Between 0.132 and 0.145 for short cycles and between 0.105 and 0.108 for long cycles.)

These results indicate that in the trading cycle method, if pursuing uniform benefits for all farmers regardless of the scale, an algorithm that allows exchange of the expanded main plots and selects longer cycles is desirable. This method is, however, associated with a rather lower rate of consolidation for larger-scale farmers. If intending to strongly promote consolidation of these farmers, selecting shorter cycles is recommended.

6. Conclusion

This paper, positioning the issue of farmland consolidation through plot exchange as a problem of indivisible goods exchange, verified by simulation to what degree consolidation would be actually possible.

The simulation showed that where farmers conduct direct, decentralized exchanges, as they currently do, a farmer owning 2 ha or more farmland is able to find, with a probability of 80 % or higher, at least one exchange partner with whom the double coincidence of wants is directly satisfied. However, we also found that to achieve consolidation, there should be many such matching pairs, and thus it is difficult to promote consolidation through direct exchange. To be specific, if a quarter of the farmers of a village participate in exchange, only very few successful matchings occur, with a consequent consolidation rate of nearly zero. Even with participation of half of the farmers, the rate remains at around 4% . With participation by all farmers, the consolidation rate reaches around 40% in the case with most generous conditions (allowing exchange of the expanded main plots).

To achieve a higher consolidation rate, this paper proposes a collective, centralized method in which multiple farmers bring their plots they want to exchange with others and exchange all the gathered plots at one time. While the consolidation rate of this method is lower than 1% when the participation rate is as low as 25% even in the case of allowing exchange of the expanded main plots, the rate dramatically rises as the participation rate increases; to around 10 % when half of the farmers participate, around 40% with participation by 3/4 of farmers, and over 95% when participated by all farmers. This is because farmers can agree to submit their plots for other farmers with whom double coincidence of wants is not directly satisfied, as they are assured of being able to obtain the plots connected to their main plots through simultaneous exchange within a cycle formed by multiple farmers.

Based on these results, it is politically recommended to invite as many farmers as possible and set many opportunities for collective, centralized distribution.[18] Possible measures include having a mediator such as an agricultural cooperative or an agricultural land holding rationalization corporation call for participation in a simultaneous exchange, and having farmers desiring exchange of their plots invite other farmers to participate.

Incidentally, discussions of this paper on the farmland consolidation issue based on simulation reserve the following points: First, while this paper simulated the algorithms in which outlying plots are always turned into plots adjacent to the main plots, there is a possibility of further reducing the number of the consolidated plots by connecting them to the consolidated plots other than the main plots. Second, although in the simulation all plots are considered as equal-level goods, they are actually different in terms of the area and quality, and therefore the actual negotiations are likely to be quite difficult. As a practical measure, it may be effective to first complete reallocation without considering the differences between plots and later financially settle the changes from before and after exchange.

In this paper, the issue of farmland consolidation through plot exchange is positioned as a problem of indivisible goods exchange. Compared with the well-known housing market problem, this problem is more complicated as it is associated with complementarity in plural units, and allows farmers to have indifferent preference and change their preference dynamically. Our remaining tasks include theoretically characterizing this type of indivisible goods exchange problem and to develop more desirable allocation algorithms.

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18) This is similar to "*warichi*," a land replotting measure implemented periodically in some regions in the early modern times (Watanabe *et al.*, 2002), though the major purpose of *warichi* is said to have been leveling of the burden of taxes and risks.

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