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最適伐期決定理論研究の発展過程

The development process of research into the theory for the determination of optimal harvest age

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要旨：最適伐期決定理論は，森林所有者の施業目的を満足させる伐期を決定するための理論である。本論文では最適伐期決定理論に関わる重要な先行研究を整理するとともに過去の研究から得られる知見を明らかにした。最初に初等的なファウストマン理論の考察を行い，最適伐期は伐期延長の限界利潤と機会費用が均衡する時点であるという結論を得た。初等的なファウストマン理論を他の理論と比較した研究としてはサミュエルソンの研究を整理した。サミュエルソンの議論からはファウストマン理論は代表的な最適伐期決定理論の中では最も優れた理論である一方，三つの課題を指摘できることが明らかになった。更にサミュエルソン以降の研究を概観し，ファウストマン理論に基づいた先行研究を五つのグループに分類し，ファウストマン理論研究の発展経路を明らかにした。五つの研究のうち，森林の炭素吸収能を評価した研究である炭素吸収能モデルについて先行研究を整理した。結論としてファウストマン理論は初等的な理論が有する特徴を保持しながら，森林・林業にかかわる実際の問題に対する適用可能性を高める方向へと研究が発展してきたことが明らかになった。
キーワード：最適伐期決定理論，ファウストマン理論，炭素吸収能モデル

Abstract: The theory for the determination of optimal harvest age is research to decide the harvest age optimal for a landowner. In this article, we reviewed important researches about the theory and make clear the accomplishment of the theory. We first observed Faustmann theory as a fundamental theory for the determination of optimal harvest age. Through observation, we made sure that optimal harvest age is at the point where marginal benefit and opportunity cost of delaying harvest are equated. Next, we examined Samuelson's research which argued that Faustmann theory was the best among the major determination theories. By examining Samuelson's discussion, we found three problems in Faustmann theory. Through the rearrangement of the previous researches, we organized previous studies into five categories. This grouping made it possible to comprehend how the research based upon Faustmann theory has developed. Among them, carbon sequestration model (CSM) is research aiming at evaluating function of carbon storage. The problem of carbon sequestration has been studied by many researchers. We thoroughly observed the research which explicitly analyzed function of carbon sequestration. We concluded that Faustmann theory has developed into the model that is more applicable to actual issues concerning forest sector while it retains original feature of Faustmann's article.
Keywords: The theory for the determination of optimal harvest age, Faustmann theory, Carbon sequestration model

I Introduction

The theory for the determination of optimal harvest age is research to decide the harvest age optimal for a landowner. In the field of forest economics, Faustmann theory, which was established by M. Faustmann, is the fundamental theory. His paper is treated as a classical determination theory of optimal harvest age, and his idea is worth being appreciated even at present (*4*). In the last 15 years Faustmann symposium was held four times, which demonstrates the importance of the theory. However, in the field of Japanese forest economics research, there is no systematic study concerning Faustsmann theory after Akao (*1*). By reviewing previous researches discussing the Faustmann theory in the last 150 years, this article mainly

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π:Profit, T_i : Harvest Age of Period i
T^*:Optimal Harvest Age, $f(t)$: TimberVolume(m^3/ha)
C : Cost, r : Interest Rate, p : Timber Price(/m^3)
The objective function of forest owner is expressed as

$$\max_T \pi = \sum_{i=1}^{\infty} \{pf(T_i) - C\}e^{-rT_i}$$

First order condition is

$$pf'(T^*) = r[pf(T^*) - C] + r\pi$$

where e^{-rT_i} is continuous discount factor of time T_i.

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Fig. 1 Fundamental Formula of Faustmann Theory

Sources: (*4*) and (*7*)

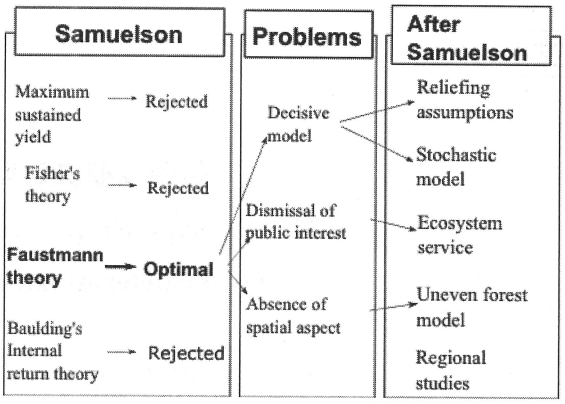

Fig. 2 The Development process of Faustmann theory

aims to clarify achievement of the theory and the problems that the theory now faces.

II Methods

Samuelson approved of Faustmann theory as the only authentic theory compared with other determination theories (*7*). Subsequently, researches shifted from proving theoretical authenticity of the Faustmann theory to modifying the theory as it suits with forest management in the real world. Furthermore, empirical researches which utilize the theory to the forest sector are also carried out. In this paper, we firstly discuss Samuelson's article to explicate the features of the Faustmann theory as a theory for the determination of optimal harvest age. In addition, we mention problems of the theory that Samuelson did not argue. Second, we review researches conducted after Samuelson's article. With these works, we illustrate the development path of Faustmann theory. Next, we analyze recent researches that evaluate externality of the function of carbon sequestration (Carbon Sequestration Model; CSM). CSM studies belong to one of the researches based on classical Faustmann theory.

III Results

1. Feature and problem of Faustmann theory

Faustmann theory formulates method how maximize the sum of present value of profits from forest management for infinite time horizon. In the model, five assumptions are made. First, timber price, interest rate and silvicultural cost are constant through the time. Second, silvicultural cost is paid just after the clear-cut of the stand. Third, initial state of the land for forest management is assumed to be bare land. Consequently, the landowner has to pay cost for planting at the beginning of the forest management. Fourth, the landowner clears the forest when it arrives at the optimal harvest age and earns revenue from timber. Finally, the landowner is assumed to repeat management cycle starting from planting and ending with harvesting for infinite times. Fourth and fifth assumptions indicate that the landowner repeatedly cuts the entire stands when they reach the optimal harvest age. According to the first order condition of profit maximization, the policy maker decide harvest age which equates the following factors: 1) marginal benefit that comes from volume increment caused by delaying the harvest for one period of time, 2) opportunity cost results from delaying harvest. Definition of the variables and detailed equations are shown in Fig. 1.

Samuelson compared Faustmann theory with maximum sustained yield theories, Fisher's theory for determination of optimal harvest age theory and Boulding's theory. He discussed each theory in terms of maximization of the present value of the profits generated from forest management. For this comparison, Samuelson used two standards: (i) valuation method of profit in different time taking account of time preference rate, (ii) accuracy of first order condition for determination of optimal harvest age. He supported Faustmann theory as the best theory from the economical standpoint since it satisfies the two standards. Samuelson's point of view has been widely accepted in the field of forest economics. It can be said that an immobile foundation was established. Its main conclusion is still referred to the basic knowledge of forest economics.

Table 1 Comparison of CSM models

	Hartman	Van Kooten et al.	Asante et al.	Hoel et al.
Evaluation of Public interests	Proportional to volume	Evaluating only carbon sequestrating function		
Time Horizon	infinite		500 years	infinite
Explanatory Variable of Carbon Sequestration	not mentioned	Proportional to growth of volume	Stock of carbon in each pools	
Carbon Stock Pool		Stand	stand/dead organic matter	stand/dead organic matter/ bio-fuel/timeber product
Beneficiary of the Externality		Forest Owner		

By using knowledge of not only economics but also other academic fields, it can be pointed out that Faustmann theory has three problems. First, it is difficult to adapt Faustmann theory to analysis of actual problems in the forest sector because it has a set of strong assumptions as well as deterministic structure. Under the assumption, it is impossible to consider the actual change of the timber price, interest rate and cost of replanting. Therefore, conducting research that takes long-term time horizon into account is difficult. Second, it regards function of timber production as the only one origin of the value of the forest. For this feature, function of public benefit never affect the decision of policy maker within the frame of Faustmann theory. As the value of ecosystem services become more and more important, it is vital to evaluate various functions dismissed in Faustmann theory. Also, forest management following Faustmann theory is highly subject to economic variables. Third, it limits the purpose of the analysis to maximization of the profit gained from a unit area of a bare land at the beginning. Therefore, the scale of management does not affect the decision making of the landowner. For example, 1ha forest management is treated as the same as that of 1,000ha. As a result, spatial variety of the forest management is not sufficiently considered. After the Samuelson's article, most of the researches have focused on the modification of these three problems and constituted new research fields.

2. The Development process of Faustmann Theory: Orientations of current researches can be sorted into 5 categories: (a) relaxation of the original assumptions of the theory to adapt to the long-term analysis, (b) introduction of stochastic factors, (c) consideration of ecosystem services, (d) uneven aged forest model and (e) studies applying the theory to the specific event in specific region. Category (a) has attempted to modify the theory by changing economic variables that are assumed to be constant through the infinite time horizon. This modification made it possible to observe the shift of optimal harvest age resulted from chronological change of economic variables. Category (b) has modified the deterministic characteristic of the theory by introducing stochastic factors. Category (c) has tried to reformulate the optimal harvest age under the condition where externality of public function of the forest is internalized. Category (d) introduces uneven aged forest model to take spatial variety into account. Category (e) is the research that tries to calculate the theoretical optimal harvest age for the specific forest management organization. The development path of the Faustmann theory is illustrated in Fig. 2

3. Current Research of CSM Research of CSM belongs to category (c). Based on Faustmann (*4*), Hartman established a new model considering recreational value, which is sum of all the values yielded by the forest other than timber production (*5*). In Hartman's discussion, recreational value is in proportion to the total volume of the forest. Hartman provided the idea of including multiple values into the Faustmann theory though forest's function of carbon sequestration is not directly discussed. Basic model of CSM was shown by Van Kooten et al. (*9*). This is the first paper to incorporate the forest's economical function of carbon sequestration. In the model, the landowner takes benefit from carbon sequestration as subsidy. The amount of the subsidy is in proportion to net volume of carbon uptake which can be expressed as gross volume of carbon sequestration minus gross volume of carbon release. The benefit landowner earns is calculated as the sum of revenue

derived from timber production and from carbon uptake.

Asante et al. and Hoel et al. developed the model of Van Kooten et al. by introducing multiple stock pool of carbon to illustrate flow of the carbon inside and outside the forest more precisely(*3*,*6*). Asante et al. emphasized the significance of the multiple carbon pools in forests. They considered living biomass in stands and dead organic matter as carbon pools. It enables them to analyze the relationship between carbon storage function of the forest and the harvest age in accordance with the theory of carbon circulation. Research by Hoel et al. was similar to the former one. But, it differed in two points. First, while Asante et al. adopted definite time horizon for the analysis, it used infinite time horizon. This difference leads to the opposite conclusion concerning carbon storage function of dead organic matter. Secondly, it had larger number of carbon pools. While Asante et al. set only two carbon pools in the model, it added bio-fuel and timber product to the carbon pools. This modification made it possible to observe how much carbon can be stocked outside forests.

CSM has two theoretical implications. First, it expands the range of Faustmann theory by analyzing optimal harvest age under the condition where both timber production and carbon sequestration is evaluated. Secondly, it incorporates carbon flow into Faustmann theory. On the other hand, two problems persist in CSM. First, it sets assumption that is different from actual forest. More specifically, it assumes that there is no stand at the beginning and thinning is not regarded at all. Secondly, redistribution of the benefit results from the function of carbon uptake is not discussed.

IV Concluding remarks

Through the review of research, the Faustmann theory has developed into the model that is more applicable to analyzing theoretical dimension of the actual issues concerning forest sector while it retains original feature of Faustmann's article. On the other hands, it is difficult to apply Faustmann theory to individual forest management because the model is built for observing correlation between optimal harvest age and economic variables. For this feature, if researches of the Faustmann model are continued, it would be hard to include non-economic variables. Namely, it seems difficult to take regulation of the planting or regional convention into account within the Faustmann model.

In the case of CSM, it is expected to contribute to the mechanism designed for REDD+. With knowledge obtained from the CSM researches, the system of giving incentive can be modified to the one that conforms to the actual carbon circulation.

The researches of this field are not sufficient in Japan. That is because most of the models are constructed without considering factors that is important in forest management in Japan. Among researches conducted by Japanese, Tanaka modified Faustmann theory by considering variation of the initial stock of the forest *(8)*. It is necessary to modify the theories to take account of the reality of forestry in Japan.

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