New weeding strategies towards low-cost silviculture of sugi (Cryptomeria japonica)plantations.

福本, 桂子

https://doi.org/10.15017/1931966

出版情報：九州大学, 2017, 博士（農学）, 課程博士
バージョン：
権利関係：

New weeding strategies towards low-cost silviculture of sugi (*Cryptomeria japonica*) plantations

Dissertation

Keiko Fukumoto

2018

Kyushu University

Contents

Chapters

Chapter 1. General Introduction

1.1. General introduction

Weeding has an important role for sustainable forest management. Weeding is conducted to prevent the competition for light, nutrients, and soil water between planted trees and weed (Wagner et al. 2006; Dacosta et al. 2011). Therefore, weeding has a direct relation to the growth of planted trees (e.g. Mallik et al. 2002; Miller et al. 2003; Homagain et al. 2011a). There are various weeding methods in the world. For example, there are herbicides treatment (e.g. Wagner et al. 1999; Stokes and Willoughby 2014; Scarbrough et al. 2015), aerial treatment (e.g. Pitt et al. 1999; Homagain et al. 2011b), mechanical treatments (e.g. Franceschi and Bell 1990; Wiensczyk et al. 2011; Thiffault et al. 2014), fire treatment (e.g. Korb et al. 2012; Strahan et al. 2015), mulch or mat treatment (e.g. Mason 2006; Wiensczyk et al. 2011) and biocontrol (e.g. Pitt et al. 1999; Roy et al. 2010). The manual treatments with brush-cutter is widely adapted in the case of Japanese forestry (Forestry Agency 2016). This method is usually conducted at least once or twice per year for 5 or 6 years after planting (Kawana and Kataoka 1981). The manual treatment with brush needs repetitive treatment because of weed rapid regrowth. Thus, this method results in high costs, accounting 40% of the total cost during the first 10 years after planting (Yukutake and Yoshimoto 2001). Therefore, the reduction of weeding cost is important theme in Japan.

1.2. Literature review

Several studies have already reported on weeding operation in the world. For example, some studies focused on the relationship between various weeding methods, such as herbicides treatment and mechanical treatment with brush-cutters, and growth of planted trees for sustainable forest managements (e.g. Mallik et al. 2002; Miller et al. 2003; Homagain et al. 2011a). Those results implied that weeding operation was important for growth of planted trees in most cases (e.g. Biring et al. 2003; Dacosta et al. 2011; Stokes and Willoughby 2014; Thiffault et al. 2014). On the other hands, several countries tended to avoid using herbicides for protection of forest ecosystem and human health (Little et al. 2006; Thiffault and Roy 2011). Thus, the other weeding methods that replace using herbicides were examined by several researchers (e.g. Thiffault and Roy 2011; Homagain et al. 2011b). For example, Homagain et al. (2011b) compared the effects of herbicide treatment, brush-cuter treatment, mechanical treatment using tractor and line cutting on planted white spruce stand growth, and they showed that timber quality did not differ significantly among weeding methods.

The details of weeding in each country were summarized by two papers (Little et al. 2006; Wagner et al. 2006), and these papers stated that each country had some problems and future prospects of weeding operation. Also, these papers implied that the optimal weeding method was different in each country due to differences of tree species, weeds compositions and micro climate. Therefore, the development of optimum weeding methods and strategies are needed in each country and region.

In the case of Japan, many researchers took on various weeding studies for the reduction of weeding cost. For example, studies focused on weeding methods such as partial cutting (Tange et al. 1993; Ito et al. 2015), season when weeding was conducted (Itou and Yamada 2001), laying seat or mulch (Uemura and Taniguchi 2004), competition between planted trees and surrounding weed under saving weeding treatment (Kitahara et al. 2013; Yamagawa et al. 2016) and reducing weeding frequency (e.g. Akai et al. 1987;

Kinjou et al. 2011a; Kinjou et al. 2011b; Hirata et al. 2012; Fukumoto et al. 2015). Especially, some papers compared the effects of only two treatments; annual or non-weeding, but there have been few studies examining the effects of various weeding frequency and schedules (Akai et al. 1987; Hirata et al. 2012; Fukumoto et al. 2015b).

Several researchers reconsider the reduction of weeding frequency for developing a new low-cost silviculture system. Especially, some papers examined criterion when weeding operation can be completed (Ogata and Nagatomo 1971; Sakura 1987; Tsurusaki et al. 2016; Yamagawa et al. 2016). For example, Ogata and Nagatomo (1971) and Sakura (1987) indicated that weeding can be completed when sugi planted trees reached at the height of 1.5 m and 2.0 m, respectively. Yamagawa et al. (2016) investigated competition between sugi planted trees and weed, and they described that sugi height growth decreased when sugi was covered by weed completely. Thus, we should construct weeding criteria so that planted trees does not overtop weed for avoiding the reduction in planted trees growth after completing weeding. However, the previous weeding completion criteria have not considered subsequent growth of both planted trees and weed after judging the necessity of weeding operation.

1.3. Objectives

The weeding strategies such as weeding frequency, schedule and weeding completion criteria towards low-cost silviculture system has not been clarified from tree mortality rate, planted trees growth and weeding operation time. Therefore, it is not clear that how many times we can reduce weeding frequency from those viewpoints. Also, the weeding completion criteria that considers subsequent sugi and weed growth after weeding completing has not been examined. The main objective in this study is to develop the new strategies including weeding frequency, schedules and weeding completion criteria. To achieve this objective, we examined: (1) the effect of weeing frequency on plated trees survival rate, (2) the effect of weeing frequency and schedules on sugi height growth, (3) the effect of weeing frequency and schedules on weeding operation time, (4) the optimum weeding schedules and (5) the weeding completion criterion for judging necessity of weeding operation.

1.4. Study site

Study site

The study site was the Takakuma Experimental Forest of Kagoshima University, located on the Osumi Peninsula in southwestern Japan (Figure 1.1). The experimental forest has a total land area of 3,066 ha. This area was located on a steep slope with an average inclination of 20.95°, and its elevation ranges from approximately 100 to 885 m above sea level. The climate is characterized as warm-temperate zone. Annual mean temperature and precipitation were 15°C and 2,800 mm, respectively. The natural vegetation of this area consisted of an evergreen broadleaved forest dominated by *Quercus acuta*, *Lithocarpus edulis*, *Castanopsis sieboldii*, and *Distylium racemosum*. Thirty-seven percent of the experimental forest covered by managed forests composed of sugi (*Cryptomeria japonica*) and hinoki (*Chamaecyparis obtusa*). These managed forests are mainly even-aged forests that were planted in the 1960s after clearcutting of coppices for fuelwood. The soil type of this area categorized into black soil.

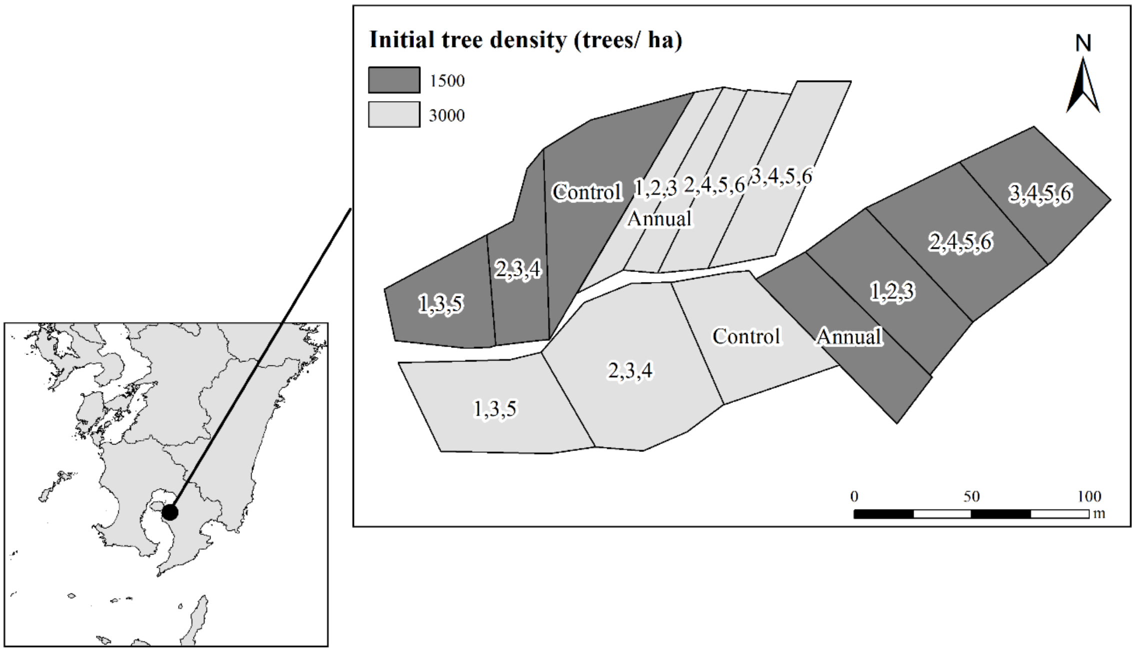

Figure 1.1. Location and arrangement of study blocks. The numbers in the figure indicates weeding schedules.

Experimental design

In May 2006, 2.57 ha were clearcut. Prior to clearcutting, the area was composed of managed sugi and natural broadleaved forests. The clearcutting area was located in an east–west valley with an inclination of 15–41° at an elevation of approximately 600 m above sea level. Thus, the clearcutting area included north-facing and south-facing slopes. In March 2007, sugi saplings were planted at initial planting density 1,500 (trees/ha) and 3,000 (trees/ha) (Table 1.1). Each initial planting density site was divided into seven plots with different weeding schedules. In plot (1), the management treatments were conducted annually for six growing seasons (i.e., 2007–2012). In plot (2), weeding treatments were conducted in years 2, 4, 5 and 6 (i.e., 2008, 2010, 2011, and 2012). In plot (3), the weeding treatments were conducted in years 3, 4, 5 and 6 (i.e., 2009–2012). In plot (4), weeding treatments were conducted in years 1, 3 and 5 (i.e., 2007, 2009, and 2011). In plot (5), weeding treatments were conducted in years 2, 3 and 4 (i.e., 2008–2010). In plot (6), weeding treatments were conducted in years 1, 2 and 3 (i.e., 2007–2009). In plot (7), no weeding treatments were conducted during the six growing seasons (Table 1.1) (Figure 1.1). There were 14 different plots in the study area (seven management treatments for each tree spacing). All of the weeding treatments were conducted using a brush cutter in early summer. In this study, we defined "weed" as plants other than planted sugi. The majority weed at this study area were shrub such as *Mallotus japonicus*, *Rhus javanica var. chinensis*, *Zanthoxylum ailanthoides*, *Aralia elata*, *Machilus thunbergii* and *C. sieboldii*. *Miscanthus sinensis* (pampas grass) was found in some areas (Kinjou et al. 2012).

.

Table 1.1. Timing (years after planting) of weeding, block area, slope aspect and initial planting density. Open circles indicate the implementation of weeding during the indicated year.

Block number	Weeding frequency	Weeding implement year 1	2	3	4	5	6	Block area (ha)	Slope aspect	Initial planting density (trees/ha)
1	6	○	○	○	○	○	○	0.15	N	1,500
2	4		○		○	○	○	0.25	N	1,500
3	4			○	○	○	○	0.16	N	1,500
4	3	○		○		○		0.18	N	3,000
5	3		○	○	○			0.33	N	3,000
6	3	○	○	○				0.25	N	1,500
7	0							0.21	N	3,000
8	6	○	○	○	○	○	○	0.11	S	3,000
9	4		○		○	○	○	0.21	S	3,000
10	4			○	○	○	○	0.09	S	3,000
11	3	○		○		○		0.18	S	1,500
12	3		○	○	○			0.17	S	1,500
13	3	○	○	○				0.08	S	3,000
14	0							0.20	S	1,500

Chapter 2. The effect of weeding frequency on the mortality and accidental cutting of planted sugi trees.

2.1. Introduction

Recently, several studies have been seeking for a possibility to reduce weeding frequency in Japan, towards low-cost silviculture. These studies discussed reducing of weeding frequency in terms of planted trees growth (Akai et al. 1987; Kinjou et al. 2011a; Hirata et al. 2012; Fukumoto et al. 2015b; Yamagawa et al. 2016) and cost of weeding operation (Kinjou et al. 2011b; Kitahara et al. 2013). However, few studies focused on survival rate of planted trees. It is likely that the survival rate of planted trees decreases by the reduction of weeding frequency. As a result, the number of trees that can be harvested decreases when the survival rate decreases. Thus, we need to clarify relationship between reduction of weeding frequency and survival rate of planted tree.

There are two factors of reducing the tree survival rate. One is the mortality that is caused by competition with weed. For example, Hiraoka et al. (2013) showed that tree mortality of sugi clones was low regardless of weeding operation. This study mainly compared the mortality under the condition of non-weeding and annual weeding, but the effect of reducing the weeding frequency on tree mortality was not quantified. The other factor is accidental cutting caused by human error. Several studies reported that accidental cutting was caused due to low visibility by thick weed (Kinjou et al. 2011a; Ukon and Takeuchi 2011). Yokoi (2001) showed that accidental cutting rate was high when weeding frequency was reduced in Japanese zelkova (*Zelkova serrata*) stand. Similarly, various studies investigated the relationship between weeding operation and accidental cutting in broad-leaved stand (Maeda 1999; Yokoi et al. 1999). However, few studies clarified the accidental cutting in coniferous stands such as sugi or hinoki (*Chamaecyparis obtsusa*) stands.

Generally, weed structure such as species composition and weed size depend on slope aspect and initial tree density. Therefore, these factors may affect tree mortality. Similarly, weed size may affect visibility of weeding operation. Thus, accidental cutting rate was indirectly affected by slope aspect and initial tree density. However, few studies discussed about the effects of slope aspect and initial density on tree mortality and accidental cutting rate under reducing weeding frequency.

In this chapter, we investigated the effects of weeding frequency, slope aspect and initial tree density on rate of tree survival, mortality and accidental cutting. First, we compared mortality rate and accidental cutting rate of 7 years-old sugi saplings with different weeding schedules. Finally, to predict the probability of mortality and accidental cutting in different weeding frequencies, we applied the multinomial logistic regression model using weeding frequency, slope aspect and initial tree density as explanatory variables.

2.2. Materials and Methods

Study site and Measurements

The study site was the Takakuma Experimental Forest of Kagoshima University, located on the Osumi Peninsula in southwestern Japan. The details of our study site were referred to the pervious chapter 1. The tree mortality and accidental cutting in study plots were visually confirmed when weeding operation in all study plots had been completed in November, 2012 (Table 2.1, Table Appendix 1, 2). Then, accidental cutting was defined as stem cut off by brush cutter.

Table 2.1. Summary of study plot and weeding implementation year.

	Weeding freqency	Initial planting density (ha/ trees)		Plot area (ha)		The number of sugi		Slope gradient (°)	
		North	South	North	South	North	South	North	South
Every year	6	1,500	3,000	0.15	0.11	63	62	34	36
2・4・5・6	4	1,500	3,000	0.25	0.21	62	61	33	33
3・4・5・6	4	1,500	3,000	0.16	0.09	60	60	31	32
1・2・3	3	1,500	3,000	0.25	0.08	60	62	34	36
1・3・5	3	3,000	1,500	0.18	0.18	61	61	15-41	37
2・3・4	3	3,000	1,500	0.33	0.17	57	60	37	37
Non weeding	0	3,000	1,500	0.21	0.2	66	60	37	36

Data analysis

First, we summarized the descriptive statistics for the effect of weeding frequency, weeding schedule, slope aspect, initial tree density on tree mortality rate and accidental cutting rate using field data. Secondly, we used multinomial regression model to simulate survival rate, mortality rate and accidental cutting rate under different weeding frequency, slope aspect, and initial tree density. The explanatory variables were slope-aspect (*NS*), initial tree density (*D*), weeding frequency (*F*), and each interaction effects ($NS \times D$; $NS \times F$; $D \times F$). Then, we used the dummy variable that takes a value of 1 if slope aspect was north-facing slope and otherwise, the value 0. Finally, we selected the model on the basis of Akaike's information criterion (AIC). The selected model was used for prediction of sugi survival, mortality and accidental cutting rate with different weeding frequency. This statistical analysis was done using the VGAM package in the R 3.1.3 software package (Yee 2010; R Core Team 2014).

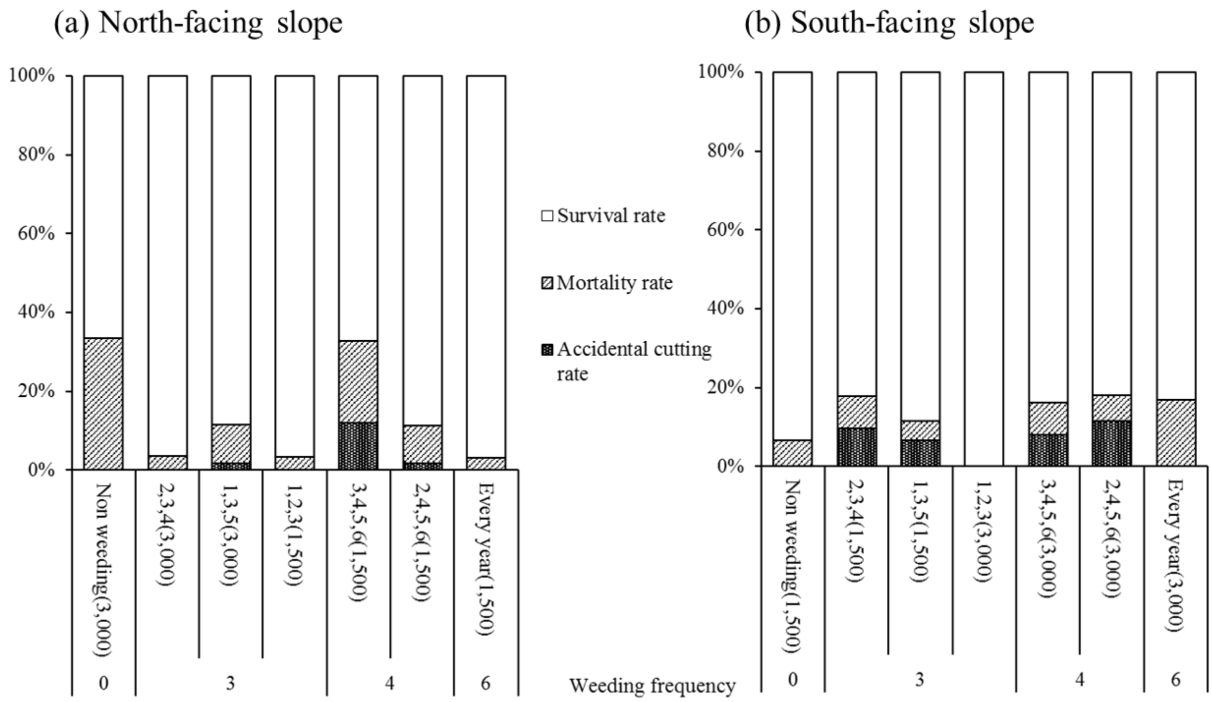

Figure 2.1. The 7 years old sugi survival, mortality and accidental cutting rate with different weeding frequency and schedule.

2.3. Results

The effect of different weeding frequencies and schedules on sugi mortality and accidental cutting

Figure 2.1 showed that 7 years-old sugi survival, mortality and accidental cutting rate with different slope aspects. On north-facing slope, sugi survival rate was 66.7 –96.8 %. The sugi mortality rate was the highest when weeding was not conducted. In contrast, the sugi mortality rate was the lowest when weeding was conducted every year. The sugi mortality rate with four-treatment weeding frequency was higher than that of three-treatment weeding frequency, and it was especially high with weeding treatment in years 3, 4, 5 and 6. The sugi mortality with three-treatment weeding frequency was 3.3 %–9.8%, and sugi mortality was especially low with weeding treatment in years 1, 2 and 3. The accidental cutting rate was the highest with weeding treatment in years 3, 4, 5 and 6

(12.1 %). The accidental cutting was also found in three-treatment weeding frequency; the rate was 1.6 %. The accidental cutting was not found with weeding treatment in every-year or years 1, 2 and 3.

On the south-facing slope, the sugi survival rate was 82.0 –93.3 %. Sugi mortality rate was the highest when weeding was conducted every-year, representing 16.9 %. The sugi mortality rate of the plots except for every-year and in years1, 2 and 3 was 4.9 –8.6 % regardless weeding frequency. The accidental cutting occurred when weeding conducted three and four times; these rate were 6.5 –11.4 %. Both the slope aspects, the accidental cutting did not occur with weeding treatment in every-year or in years 1, 2 and 3. On each slope, the sugi mortality and accidental cutting rate was not found a clear difference between initial planting densities.

The effect of weeding frequency, slope aspect and initial planting density on tree mortality and accidental cutting.

The selected model included *NS*, *D* and $NS \times F$ (Table 2.2). For mortality, *S* and $NS \times F$ were significant (p <0.05), but not significant (p >0.05) for accidental cutting. *D* was not significant for both mortality and accidental cutting (p >0.05).

The predicted sugi survival rate on north-facing slope increased with increasing weeding frequency (Figure 2.2). The survival rate of six-treatment weeding frequency on initial tree density of 1,500 (tree/ha) and 3,000 (trees/ha) were 95.3 % and 97.8 %, respectively. In the case of non-weeding, the survival rate for initial tree density 1,500 (trees/ha) and 3,000 (trees/ha) were 55.1 % and 69.5 %, respectively. The predicted mortality rate decreased with increasing weeding frequency, and the mortality rate of six-treatment weeding frequency with the initial tree density 1,500 (trees/ha) and 3,000

Table 2.2. Summary of parameters incorporated in the selected model.

	Description	Coefficient	SD	p -value
Mortarity	intercept	-1.9819	0.5104	< 0.05
	NS	2.3462	0.3846	< 0.05
	D	-0.0004	0.0002	0.06
	$NS \times F$	-0.5281	0.1074	< 0.05
Accidental cutting	intercept	-2.2588	1.0141	< 0.05
	NS	-0.2040	1.3672	0.88
	D	-0.0008	0.0005	0.09
	$NS \times F$	-0.0692	0.3313	0.83

(tree/ha) were 3.1 % and 1.7 %, respectively. The predicted mortality rate tended to increase when initial tree density was 1,500 (tree/ha). The predicted accidental cutting rate occurred regardless of weeding frequency. On the south facing slope, the sugi survival, mortality and accidental cutting rate were invariable regardless of weeding frequency; the rates were 90.4 %, 6.8 % and 2.7%, respectively. In the case of tree initial density of 3,000 (tree/ha), these rates were 95.2 %, 3.9 % and 0.8 %, respectively.

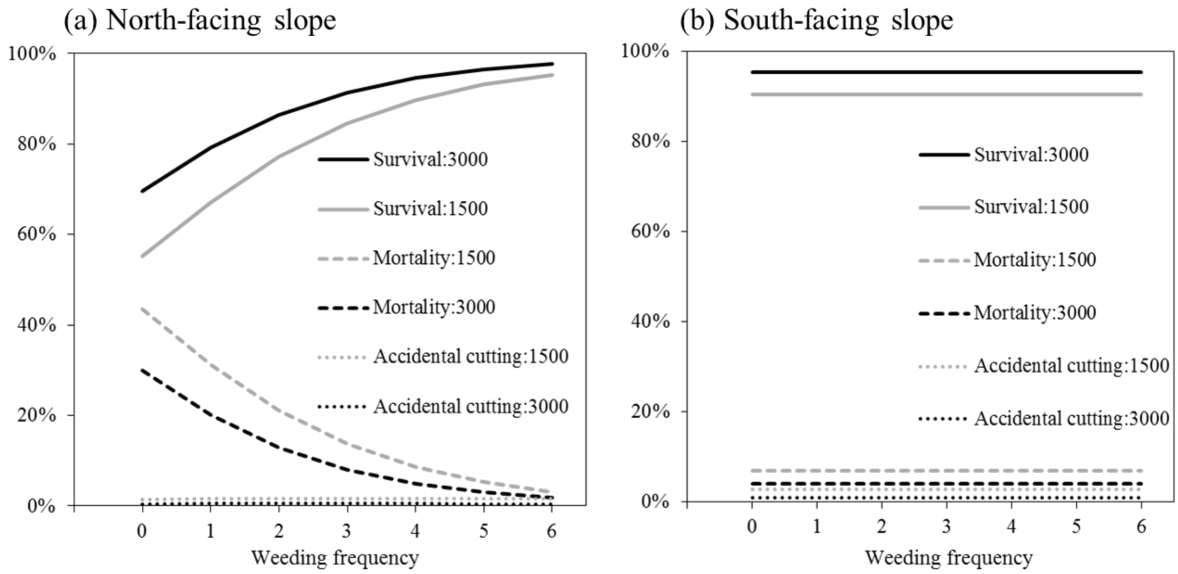

Figure2.2. Predicted sugi survival rate, mortality rate and accidental cutting rate under different weeding frequency. (a) North-facing slope, (b) South-facing slope.

2.4. Discussion

The sugi mortality varied depending on weeding frequencies, weeding schedules and slope aspects (Figure 2.1). In general, weeding plays an important role for reducing competition of planted trees with weeds for light, soil water and soil nutrients (Wagner et al. 2006). On the one hand, weeds protect planted trees against aridity and high temperature of grand surface (Sakaguchi 1983). One possible reason why slope aspect affected the sugi mortality was the difference of vegetation. For example, pampas grass (*Miscanthus sinensis*) invaded on south facing slope (Fukumoto et al. 2015b), while broadleaved trees such as pioneer invaded on north facing slope (Kinjou et al. 2011b). Shigenaga et al. (2012) reported that sugi planted trees growth declined by covered pampas grasses. On the other hand, Tanimoto (1982) reported that sunlight transmitted more through pampas grass stand than broadleaves trees. Therefore, sugi growth was low when weeding was not conducted on south facing slope, because sugi could receive much more light in comparison with north facing slope. The mortality rate on south facing slope was higher than that on the north facing slope when weeding was conducted in every year. Weeding conducted in every year might cause a decline in weed protecting role, and therefore the mortality rate under weeding conducted every year was higher than any other schedules on south facing slope. These results suggest that we should judge suitable weeding frequency and schedule depending on slope aspects.

On north facing slope, the mortality rate was high when weeding was not conducted, and the rate was low when weeding was conducted every year. Additionally, the mortality rate with four-treatment weeding frequency was higher than the three-treatment weeding frequency. These results suggest that the mortality is not always low with more weeding frequency, and the mortality may be affected by weeding schedules. The sugi mortality rate was high when weeding was conducted only once three years after planting (e.g. treatment in years 3, 4, 5 and 6 or years 2, 4, 5, and 6). This result showed that weeding conducted at least twice in three years after planting is important for reducing tree mortality rate.

The accidental cutting rate was not different among weeding frequency and between different slope aspects. These results suggest that accidental cutting occur a certain number regardless of weeding frequency and slope aspect. However, weeding conducted in every year and in years 1, 2 and 3 did not cause accidental cutting on each slope aspect. Ukon and Takeuchi (2011) reported that weeing conducted during consecutive year could reduce accidental cutting. Therefore, the accidental cutting rate in the plots where weeding conducted consecutive year just after planting was low. On the other hand, the accidental cutting rate was high with weeding treatment in year 3, 4, 5 and 6, because visibility was declined due to invaded weeds. These results suggest that we had better practice weeding during two years after planting to reduce accidental cutting.

The multinomial regression model showed that slope aspect, initial tree density and interaction effect of weeding frequency and slope aspect were selected as significant explanatory variables (Table 2.2). On tree mortality rate, $NS \times F$ was significant ($p < 0.05$). This result showed that the tree mortality rate for each weeding frequency was different between slope aspects. The tree mortality rate on north-facing slope depends on each weeding frequency (Figure 2.2). Therefore, we have to consider lack of certain amount of planted trees by mortality when weeding frequency is reduced. Yet in south facing slope, the tree mortality was invariable regardless of weeding frequency (Figure 2.2). Therefore weeding frequency should be reduced in comparison with the conventional weeding frequency. For the accidental cutting rate, all selected variables were not significant (p >0.05) (Table 2.2). Therefore, we conclude that accidental cutting occurs regardless of weeding frequency and slope aspects. In contrast, initial tree density was selected as explanatory variables on tree mortality and accidental cutting model; however, the variables were not significant (p >0.05) (Table 2.2). Nevertheless, predicted sugi mortality and accidental cutting rate under initial planting density 1,500 (trees/ha) were higher than that with 3,000 (trees/ha) (Figure 2.2). Tsutsumi (1994) suggested that replanting is needed when tree mortality rate in the year after planting was more than 20 % for initial tree density of 3,000 (trees/ha) stand. The logistic regression analysis showed that the mortality rate was more than 20 % when weeding was conducted two times or less under 3,000 (trees/ha), or weeding was conducted three times or less for 1,500 (trees/ha). If we follow the suggestion by Tsutsumi (1994), weeding would need at least two times. Furthermore, our result suggested that planted trees mortality and accidental cutting could be reduced if weeding is conducted two times during 3 years after planting.

This chapter focused on the effects of weeding frequency, schedule, slope-aspect and initial plating density on sugi mortality and accidental cutting. In term of mortality rate, we have to consider the optimum weeding schedule depending on slope aspect and initial planting density. The accidental cutting may occur everywhere, and therefore we must be careful for initial setting for the number of trees. On the other hand, our result suggested that sugi mortality and accidental cutting rate increase depending on weeding schedules. The plot where weeding was conducted in years 3, 4, 5 and 6 had high mortality and accidental cutting rates. This result suggests that survival rate significantly decreased when weeding was not conducted two years after planting. Our statistical model could not explain the optimum weeding schedules in terms of sugi mortality and accidental cutting rate. We will have to clarify the optimum weeding schedule taking into account conditions such as slope aspect and initial tree density. Moreover, weeding schedules might affect tree growth and weeding operation time (Wagner et al. 1999; Kinjou et al. 2011a), and so we will have to comprehensively clarify the effect of weeding schedules on tree growth and operational cost.

Chapter 3. The effect of weeding frequency and timing on the height growth of young sugi stands.

3.1. Introduction

Weeding cost reducing is important subject in Japan. Because, weeding cost account approximately 40 % for management cost in early stage. On the other hand, Weeds grow rapidly and may compete with planted saplings without appropriate weeding. As a result, one cannot avoid the growth suppression from weeds when one reduces the number of weeding. Thus, one has to establish a weeding schedule under which the growth suppression from weeds, as well as the number of weeding, is minimized. Several studies have focused on reducing the number of weeding of sugi and hinoki (Akai et al. 1987; Shimozono et al. 2009; Kinjou et al. 2011a; Hirata et al. 2012; Fukumoto et al. 2015b). These studies mainly focused on non-weeding or annual weeding, and they showed that the growth of planted trees decreased under the non-weeding (Akai et al. 1987; Hirata et al. 2012). However, the effect of weeding on the growth of planted saplings were not quantified.

Our main objective in this chapter is to investigate the effect of weeding schedules on the height growth of sugi saplings. To achieve this objective, we developed stand-level sugi and weed annual height growth models that accounted for tree spacing, slope aspect, and the prior heights of sugi and weeds. Finally, we simulated sugi height under different weeding scenarios and consistent conditions in terms of tree spacing and slope aspect.

3.2. Materials and Methods

Study site and Measurements

Our study site was Kagoshima University experimental forests. The detail of description our study site referred to chapter 1. We established study plot included approximately 60 sugi saplings, and measured their heights at the end of each growing season from the first through the sixth growing seasons (i.e., 2007–2012) (Figure Appendix.1, 2). We also measured weed (i.e., broad-leaved trees/shrubs) heights from the first through the sixth growing seasons. For some plots, we randomly selected at least five places and measured the dominant height of weeds in each place from the first through the third year after planting (i.e., 2007–2009). From the four through the sixth growing seasons (i.e., 2010–2012), we randomly selected 60 places and measured the heights of dominant weeds for all plots. We defined the dominant height as the mean height of the top layer of weeds. The weeds were measured between late June and early July of the year just before the weeding was conducted.

Data analysis

Growth model

A hierarchical Bayesian model was used to determine the stand-level annual height growth of sugi and weeds. We assumed that the observed mean annual sugi and weed height growth of the *i*th plot in the *j*th growing season with a normal distribution, as follows:

$$G_{ij} \sim \text{Normal}\ \left[\ln\left(\bar{G}_{ij}\right), \sigma^2\right] \qquad (3\text{-}1)$$

where G_{ij} is the observed mean annual height growth of sugi or weeds (m year^{-1}), $\bar{G}_{ij}$ is the expected mean annual height growth (m year^{-1}) of sugi or weeds, and σ^2 is the variance of the height distribution. The mean annual height growths of sugi and weed were regressed against the explanatory variables, including mean sugi height at the end of prior growing season (*H*), mean weed height just after weeding (*WH*), the relative height of weeds to sugi (*WHH*), slope direction (*S*), sugi tree spacing (*D*), and random parameters for each plot. The developed model can be described as:

$$\ln\left(\bar{G}_{ij}^{c}\right) = \alpha_0^c + \alpha_1^c WH_{ij} + \alpha_2^c H_{ij} + \alpha_3^c WHH_{ij} + \alpha_4^c S_i + \alpha_5^c D_i + \varphi_i^c \quad (3\text{-}2)$$

$$\ln\left(\bar{G}_{ij}^{w}\right) = \alpha_0^w + \alpha_1^w WH_{ij} + \alpha_2^w H_{ij} + \alpha_3^w WHH_{ij} + \alpha_4^w S_i + \alpha_5^w D_i + \varphi_i^w \quad (3\text{-}3)$$

where $\bar{G}_{ij}^{c}$ is the expected mean annual sugi height growth (m year^{-1}), $\bar{G}_{ij}^{w}$ is the expected mean annual weed height growth (m year^{-1}), α_0^c– α_5^c and α_0^w– α_5^w are each parameter, and φ_i^c and φ_i^w are random parameters for the *i*th plot. In the case of slope direction, we defined S_i as 1 when the slope of the *i*th plot faced south; otherwise, we assigned S_i as 0. We assigned WH_{ij} as 0 when the weeding was conducted in the *i*th plot in the *j*th growing season. Thus, $\bar{G}_{ij}^{w}$ was calculated as the growth from 0 m when the weeding was conducted in the *i*th plot in the *j*th growing season. WHH_{ij} was expressed as WH_{ij} divided by H_{ij}.. WHH_{ij} was also defined as 0 when the weeding was conducted in the *i*th plot in the *j*th growing season. We assigned a normal distribution for the random parameters as follows:

$$\varphi_i \sim \text{Normal } [0, \tau] \quad (3\text{-}4)$$

where τ is the variance of φ_i. We assigned a uniform prior to τ, σ^2 and other parameters (i.e., α_0– α_5). To estimate the posterior distributions of the parameters, we used the Markov chain Monte Carlo (MCMC) method using JAGS 3.4.0 software (Plummer 2003) via the rjags package in the R 3.1.3 software package (R Core Team 2014). We obtained posterior samples from four parallel MCMC chains. For each chain, 5,000 samples were obtained with a 50,000-step interval after a burn-in period of 1,000

MCMC steps. The Gelman and Rubin $\hat{R}$ value was used to confirm the convergence of the MCMC. We set our convergence threshold at $\hat{R} < 1.1$. Model selection was conducted by a backward stepwise procedure from equations (3-2) and (3-3). We selected the model on the basis of the deviance information criterion. We calculated R^2 from observed and predicted growth of sugi and weeds. Marginal R^2, which was calculated from fixed factors alone, and conditional R^2, which was calculated from both the fixed factors and random factors were calculated, since Nakagawa and Schielzeth (2013) recommended.

Weeding simulations

We simulated sugi height after the sixth growing season under the different weeding schedules using the selected model. We assumed that sugi with a 0.6-m height was planted on a slope where site preparation had already been conducted prior to planting (i.e., the initial weed height was 0). These assumptions are based on the common situation of plantation practices in Kagoshima (Shimozono et al. 2009). The simulated weeding frequencies included the (1) non-weeding, and (2) one, (3) two, (4) three, (5) four, (6) five, and (7) six weeding during the six growing seasons. To simulate the weeding schedule, we had several choices regarding the timing of the weeding for each weeding frequency. In this study, we simulated all weeding scenarios for each weeding frequency. Weeding frequencies of zero, one, two, three, four, five, and six, yield 1, 6, 15, 20, 15, 6, and 1 combinations of their timing, respectively. In total, 64 weeding scenarios were simulated. Then, we used the tree spacing and slope aspect variables if they were included as variables in the selected model. By simulating 64 weeding schedules for their respective slope aspect (i.e., north and south), we ultimately simulated 128 weeding

Table 3.1. Summary of the parameters for the selected model.

	Parameter	Description	Mean	Marginal R^2	Conditional R^2
Sugi model	α_0^c	*intercept*	-0.22	0.72	0.79
	α_1^c	*WH*	-0.15		
	α_2^c	*H*	0.12		
	α_3^c	*WHH*	-0.65		
	α_4^c	*S*	-0.11		
	σ^2	*variance*	0.02		
Weeds model	α_0^w	*intercept*	0.38	0.27	0.31
	α_2^w	*H*	-0.09		
	α_3^w	*WHH*	-0.43		
	α_4^w	*S*	-0.30		
	σ^2	*variance*	0.16		

WH : mean weed height, *H* : mean sugi height, *WHH* : the relative height of weeds to sugi, *S* : slope direction.

schedules.

We evaluated the influence of weeding frequency on sugi height after six growing seasons, calculating the mean simulated sugi height based on the weeding frequency for the respective slope aspect. To evaluate the importance of the timing of weeding, we simulated sugi height for the three-treatment weeding frequency, because a three-treatment weeding frequency includes more choices (i.e., 20) than the other weeding frequencies. We only simulated tree height on north slopes, because the simulated heights on both slopes showed the same trend.

3.3. Results

Model selection and goodness of fit

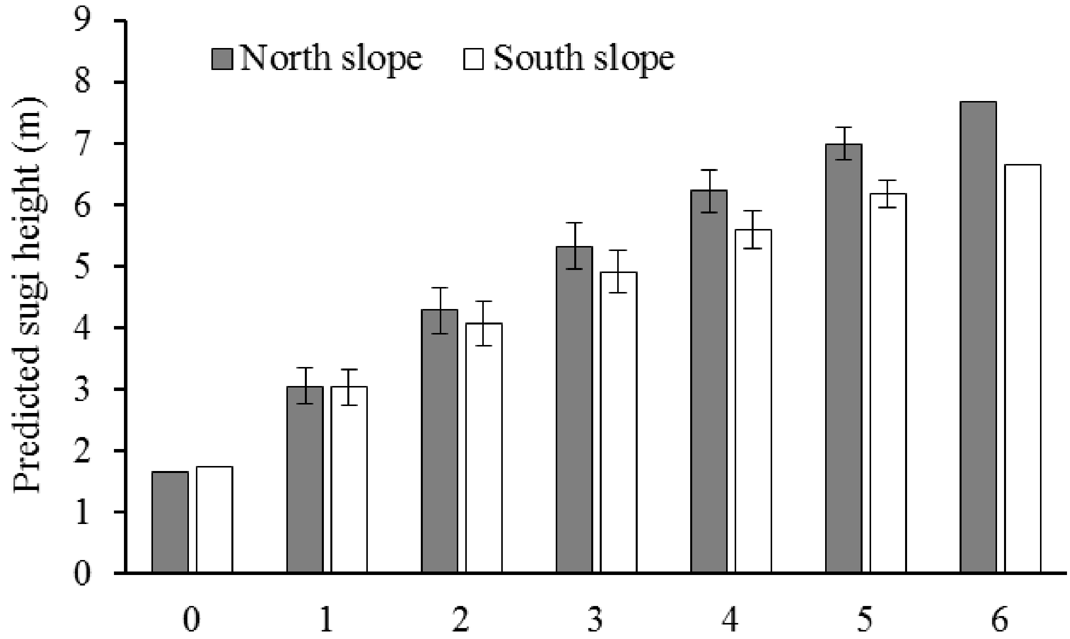

Figure 3.1. Summary of the relationship between simulated sugi height and weeding frequency. Error bars indicate standard deviations.

All of the model parameters adequately converged ($\hat{R}$ <1.1). The selected model for sugi included *WH*, *H*, *WHH*, and *S* (Table 3.1). For weeds, the selected model included *H*, *WHH*, and *S*. *D* was not selected in either model. The parameter estimates provided a good fit to the observed data. The marginal R^2 of the sugi and weed models were 0.72 and 0.27, respectively. Similarly, the conditional R^2 of sugi and weed model were 0.79 and 0.31, respectively.

Weeding scenario

The height of sugi increased with increasing weeding frequency on north- and south-facing slopes (Figure 3.1). Mean sugi height increased by approximately 20 % for every additional weeding. The height when weeding was conducted three times was

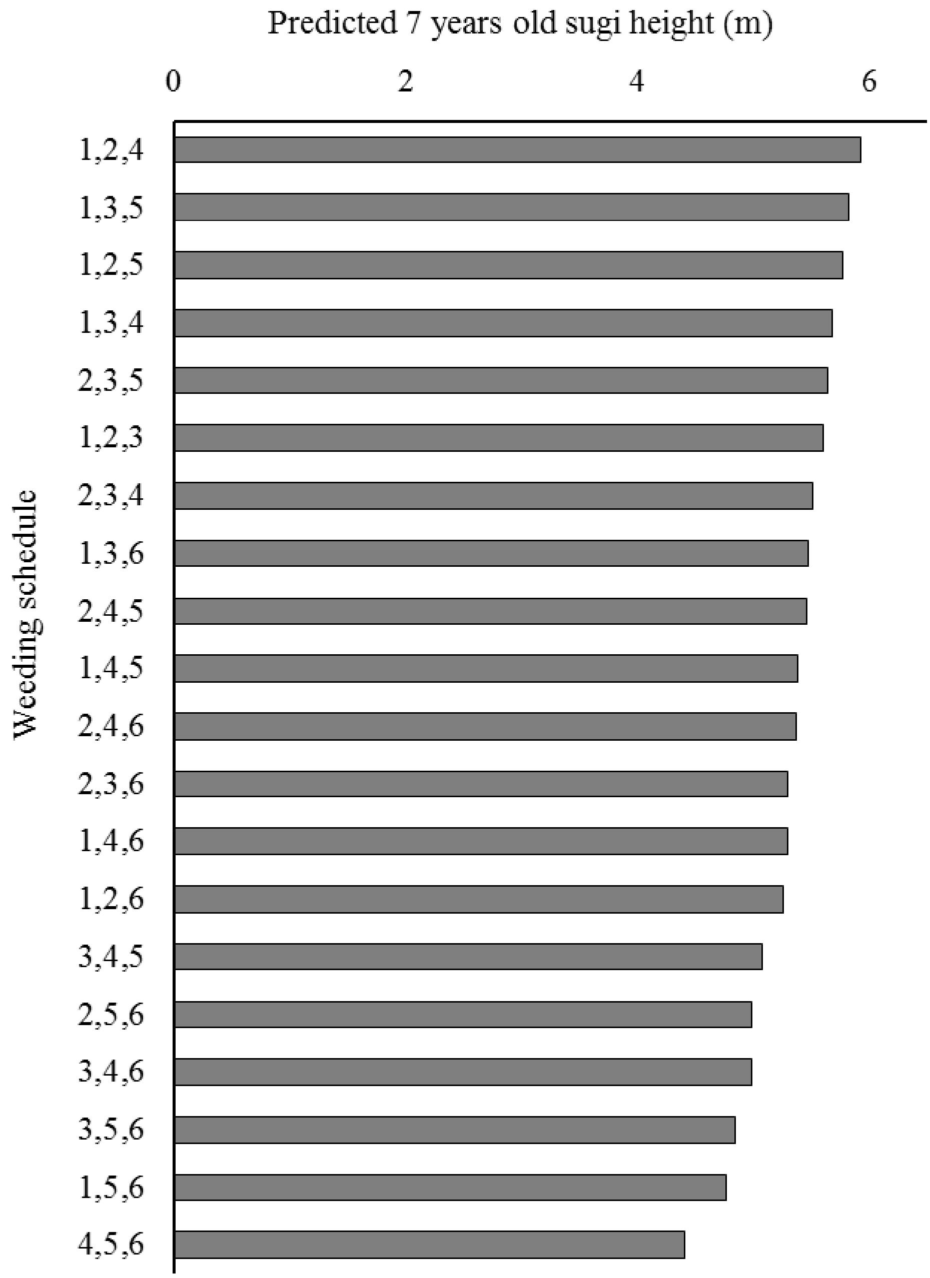

Figure 3.2. Predicted sugi height under different weeding schedules on three-treatment weeding frequencies in north facing slope.

approximately 70% of that of the annual weeding.

Sugi height was greatest with weeding treatment in years 1, 2 and 4 (Figure 3.2). Sugi height was lowest with weeding treatment in years 4, 5 and 6. When the first weeding was conducted in the third or fourth growing seasons (e.g., treatment in years 3, 4 and 5 or years 4, 5 and 6), sugi height was shorter than those of the other weeding schedules.

3.4. Discussion

Growth of planted trees is affected by weeds because of competition (Balandier et al. 2005; Kitahara et al. 2013; Hirata et al. 2015). Kitahara et al. (2013) showed that the height growth of planted sugi saplings is suppressed when the apex of the saplings is covered by weeds. This result implies that the relative heights of planted saplings and weeds may explain the interaction between sugi and weeds. Because *WHH* was selected as an explanatory variable of the model, we confirmed that the relative heights of planted saplings and weeds were important, when selecting weeding schedules. It should be noted that the coefficient of *WHH* had minus value for weeds model. This may be because the growth of weeds reach its peak after weeds height exceed the height of sugi sapling.

From the simulated results, mean sugi height increased by approximately 20 % for every additional weeding (Figure 3.1). Weeds can continually grow in the absence of weeding. As a result, sugi is suppressed by the continually growing weeds, and sugi height decreas under lower weeding frequencies. For the three-treatment weeding frequency, the sugi height was the highest with weeding treatment in years 1, 2 and 4(Figure 3.2). Additionally, according to the results of the simulation, sugi height was lowest with weeding treatment in years 4, 5 and 6. These results suggest that the timing of weeding is also important when reducing the weeding frequency. Thus, one has to consider not only the weeding frequency, but also the timing of the weeding, when reducing the weeding frequency. Furthermore, these results imply that earlier weeding is more important than later weeding. Wagner et al. (1999) proposed that weeding immediately after planting yielded better growth of planted trees compared with weeding in later years. Similarly, Mason (2006) reported that weeding in the first year after planting was the most critical for the growth of radiata pine (*Pinus radiata*) saplings. We also demonstrated that earlier weeding is more important for sugi growth.

The limitation of our model is that the model only considers the relationship between the height of sugi and weeds after weeding. Since the elongation of sugi usually starts before weeding, further study is required to develop the model taking into account the growth before and after weeding. Also, this study only focused on the relationship between the weeding schedule and height growth. However, Kinjou et al. (2011b) showed that the timing of weeding affects the time required for weeding, which was directly linked to its cost. Thus, further study is required to clarify the relationship between weeding schedules and the cost of weeding. Also, the influence of weeding on the growth of diameter and volume should be investigated.

Chapter 4. The effect of weeding frequency and timing on weeding operation time.

4.1. Introduction

Weeding is an important practice for sustainable forest management. Weeding aims to reduce competition for light, soil water and soil nutrients between planted trees and other plants. In the case of Japanese forestry, manual treatment using a brush cutter is conducted at least once or twice per year for 5 or 6 years after planting (Tsutsumi 1994). Weed control by means of a brush cutter requires repetitive treatment because of rapid weed regrowth (Biring et al. 2003). This method of weed management results in high costs (e.g. Dampier et al. 2006; Homagain et al. 2011a). For example, Homagain et al. (2011) reported stand level benefit analysis of 12 vegetation control applied in northern Ontario. They showed that the aerial herbicide control had the lowest cost (CAD\$210.50 ha^{-1}), repetitive treatment with brush cutter had the highest cost (CAD\$1750.00 ha^{-1}). In the case of Japan, weeding cost accounting for approximately 40% of the total cost during the first 10 years after planting (Yukutake and Yoshimoto 2001). Thus, reduction of the weeding cost is an important objective (Forestry Agency 2016).

Various studies were conducted for the reduction of weeding cost using various approaches in Japan. For example, some studies focused on weeding method (Tange et al. 1993; Ito et al. 2015), weeding treatment season (Itou and Yamada 2001), developing weed prevention seat (Uemura and Taniguchi 2004) and the competition between weed and planted trees (Yamagawa et al. 2016). Especially, many papers focused on the reduction of weeding frequencies (Kinjou et al. 2011a, b; Hirata et al. 2012; Fukumoto et al. 2015b), for example; the growth of planted trees under non-weeding stand (Hirata et al. 2012; Fukumoto et al. 2015) and under some weeding schedules (Kinjou et al. 2011a).

Cost is a key factor for evaluation of treatment choices, because weeding schedules must be as inexpensive as possible. Several studies have focused on the cost of weeding with a brush cutter (e.g. Kinjou et al. 2011b; Kitahara et al. 2013). Kinjou et al. (2011b) implied that weeding operation time was affected by the height of weeds and the ease with which the operator was able to recognize the planted trees. The authors suggested that the size of planted trees may affect the weeding operation time, because the operator may need to be more careful when the planted trees are small. However, the relationship between the weeding operation time and the weeds' height and the size of planted trees was not quantified. Similarly, Kitahara et al. (2013) evaluated the relationship between operation time and amount of weeds in a planted forest after the first growing season. The authors suggested that operation time of weeding was affected by the amount of weeds. However, they focused on the stand only just after the first growing season. Given that weeding is conducted for 5 or 6 years after planting, relationships between operation time of weeding and other factors in forests should be evaluated from the first to fifth or sixth growing season. In addition, factors other than the size of weeds and the ease of recognition of the planted trees should be examined. For example, the higher the initial planting density, the more operation time may be required, because operators must circumvent the planted trees. Moreover, slope aspect affects the weeding operation time due to different solar radiation. Weeding is usually conducted in early summer season when we have high temperature and humidity in western Japan. Weeding operation is one of the tough work for operators. The higher solar radiation caused physical exhaustion sever damage for operators; therefore, the factor may affect weeding operation time.

Table 4.1. Summary of field measurements data for weeding operation time (h/ha), annual sugi growth (m/year) and annual weed growth (m/year).

	Min	Mean	Max	STDV
Weeding operation time per one time (h/ha)	18.72	29.5	48.84	8.06
Annual sugi growth (m/year)	0.03	0.64	1.09	0.28
Annual weed growth (m/year)	0.06	0.96	1.99	0.45

The main objective of this chapter was to clarify the effect of weeding frequency and weeding year on the weeding operation time in a sugi stand. To achieve this objective, we developed an operation time model to account for weed height, planted sugi height, slope aspect, initial planting density and relative height of weeds to sugi saplings. We simulated the cumulative operation time under different weeding scenarios and initial planting densities using the developed model.

4.2. Materials and Methods

Measurements

Operation time of weeding

Weeding with a brush cutter was conducted once per year in early July. Three operators worked at each weeding. The same three operators conducted the weeding throughout the six-year experimental period. We recorded operation time during weeding with the brush cutter, excluding the time spent walking into the study blocks, maintaining tools, refueling and taking breaks. The operation time per hectare (h/ha) was calculated for each block area. Given that 23 weeding operations were conducted within each slope aspect (Table 1), in total we recorded operation time data for 46 weeding operations (Figure Appendix 3, 4). The operation time data were summarized in Table 4.1.

Sugi and weed height growth

We measured sugi tree height and weed height around the sugi trees in each plot from the first to the sixth growing seasons (i.e. 2007–2012). The sugi trees were measured after the growing season every year, and weeds were measured before the weeding was conducted. Detailed descriptions of the measurements are provided in chapter 3, we summarized sugi and weed annual height growth (m/year) in Table 4.1. Weed height measurements were not recorded for some plots in some growing seasons. Thus, in this study we used data for 31 weeding operations for which weed height measurements were available.

Data analysis

Operation time model

We used a hierarchical Bayesian model to determine the operation time. We assumed that the observed operation time of the *i*th plot in the *j*th implementation of weeding had a normal distribution, as follows:

$$T_{ij} \sim \text{Normal}\left[\ln\left(\bar{T}_{ij}\right), \sigma^2\right] \qquad (4\text{-}1)$$

where T_{ij} is the observed operation time per weeding treatment per hectare (h/ha), $\bar{T}_{ij}$ is the expected operation time (h/ha), and σ^2 is the variance of the operation time distribution. The explanatory variables included weed height (*WH*), sugi height (*H*), slope aspect (*S*), initial planting density (*D*) and the relative height of weeds to sugi (*WHH*; calculated as *WH* divided by *H*). *WHH* was included as an index to express the ease of recognition of sugi. The full model for operation time was expressed as:

$$\ln(\bar{T}_{ij}) = \alpha_0 + \alpha_1 WH_{ij} + \alpha_2 H_{ij} + \alpha_3 WHH_{ij} + \alpha_4 S_i + \alpha_5 D_{ij} + \varphi_i \qquad (4\text{-}2)$$

where $\alpha_0 \sim \alpha_5$ are each parameter, and φ_i is a random parameter for the *i*th plot. We assigned a normal distribution for the random parameter as follows:

$$\varphi_i \sim \text{Normal } [0, \tau] \qquad (4\text{-}3)$$

where τ is the variance of $\varphi_{i.}$ We assigned a uniform prior to τ and other parameters. To estimate the posterior distributions of the parameters, we applied the Markov Chain Monte Carlo (MCMC) method using JAGS 3.4.0 software (Plummer 2003) from within R 3.1.3 software (R Core Team 2014) with the rjags package. We ran four chains each of length 30,000 steps, after burn-in of 1,000 steps and 1/10 thinning. Following previous chapter 3, the Gelman and Rubin $\hat{R}$ and deviance information criterion (DIC) were used to confirm the convergence of MCMC and to select the best model, respectively. We calculated the root mean squared error (RMSE) and coefficient of determination (R^2) from the observed and predicted operation times. The marginal R^2 and the conditional R^2 (Nakagawa and Schielzeth 2013) were also calculated to evaluate the model following chapter 3.

Weeding simulation

We simulated cumulative operation time over the six growing seasons under the different weeding scenarios using the best model. For the simulation, we used the sugi and weed height growth models developed by chapter 2 as follows:

$$\ln(\bar{G}^c) = -0.22 - 0.15WH + 0.12H - 0.65WHH - 0.11S \qquad (4\text{-}4)$$

$$\ln(\bar{G}^w) = 0.38 - 0.09H - 0.43WHH - 0.30S \qquad (4\text{-}5)$$

where $\bar{G}^c$ is the mean annual sugi height growth (m/year), and $\bar{G}^w$ is the expected mean annual weed height growth (m/year). Detailed descriptions of the models are provided by chapter 3. Briefly, the explanatory variables include *WH*, *H*, *WHH* and *S*. The value 1 was assigned to *S* when the slope faced south; otherwise, zero was assigned. We assumed that initial planted sugi and weed height were 0.6 m and 0 m, respectively, based on our measurements. The simulated weeding frequencies ranged from one to six depending on the weeding treatment during the six growing seasons. We assigned the value zero to *WH* for estimation of sugi and weed height growth, when the weeding was conducted. For each weeding frequency, there are several options for the weeding year. In this study, we simulated all possible weeding schedules for each weeding frequency. The number of schedules for one, two, three, four, five, and six are 6, 15, 20, 15, 6, and 1, respectively. In total, there are 63 possible weeding schedules.

We simulated cumulative operation time under the different weeding frequencies under both initial planting densities (i.e. 1,500 and 3,000 trees/ha) on north- and south-facing slopes. Then, H_{ij} and WH_{ij} were calculated by the equations (4-3) and (4-4), and we substituted the values in the equation (4-2). We only present simulation results for the north-facing slope, because the simulated operation time on both slopes showed the same trend. To evaluate the effect of the weeding schedules, we focused on the three-treatment weeding frequency, following previous chapter 3. The cumulative operation time and sugi height under both initial planting densities showed the same trend. Thus, we assumed that the initial planting density was 3,000 trees/ha when we focused on the three-treatment weeding frequency.

4.3. Results

Model selection and goodness of fit

The selected model for weeding operation time included *WH, WHH* and *D* (Table 4.2). *H* and *S* were not selected in the model. The coefficients of *WH, WHH* and *D* had positive

Table 4.2. The summary of posterior distribution and parameter for selected model.

Parameter	Description	Mean	Credible interval	
			2.5%	97.5%
α_0	*intercept*	2.8310	2.4870	3.2180
α_2	*WH*	0.1740	0.0784	0.2738
α_3	*WHH*	0.2056	0.1082	0.3026
α_4	*D*	0.0001	-0.0001	0.0002
σ^2	*variance*	6.81199		

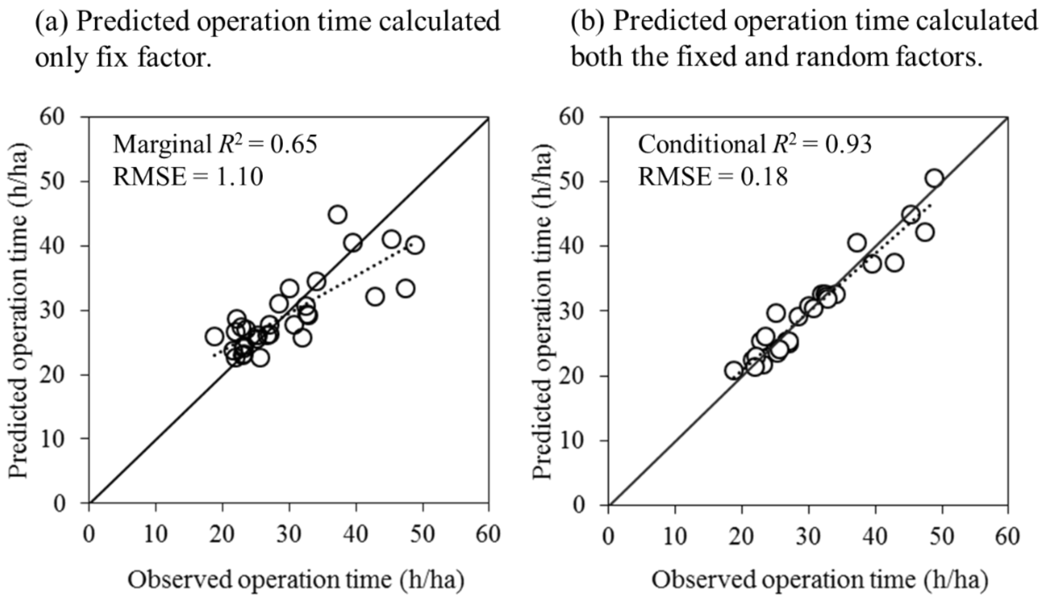

Figure 4.1. The relationship between observed operation time and (a) predicted operation time calculated only fixed factor, (b) predicted operation time calculated both fixed and random factors.

values. The marginal R^2 and RMSE values were 0.65 and 1.10, respectively (Figure 4.1(a)). The conditional R^2 and RMSE values were 0.93 and 0.18, respectively

Weeding scenario

The predicted mean cumulative operation times with annual treatment under initial planting densities of 1,500 and 3,000 trees/ha was 156 and 162 h/ha, respectively (Figure 4.2). The mean cumulative operation time with three-treatment weeding frequency under both initial planting densities was about 97 h/ha. Mean cumulative operation time decreased by approximately 6% for each one-treatment reduction in weeding frequency. Thus, if the weeding frequency was halved, the cumulative operation time was not halved.

We next focused on the three-treatment weeding frequency. Weeding treatment in years 1, 2, and 6 required the longest operation time, whereas weeding treatment in years 1, 2, and 3 required the shortest operation time (Figure 4.3). The operation time with treatment in years 1, 2, and 6 and that of treatment in years 1, 2, and 3 was 102 and 88 h/ha, respectively. These values represented 63% and 54% of that of the six-year treatment, respectively. The difference in operation time between the two scenarios was 14 h/ha. The operation time required was increased when weeding was not conducted in consecutive years (e.g. treatment in years 1, 2, and 6, or years 1, 3, and 6, or years 1, 5, and 6). In contrast, when weeding was conducted in consecutive years, the cumulative operational time decreased (e.g. treatment in years 1, 2, and 3, or years 2, 3, and 4).

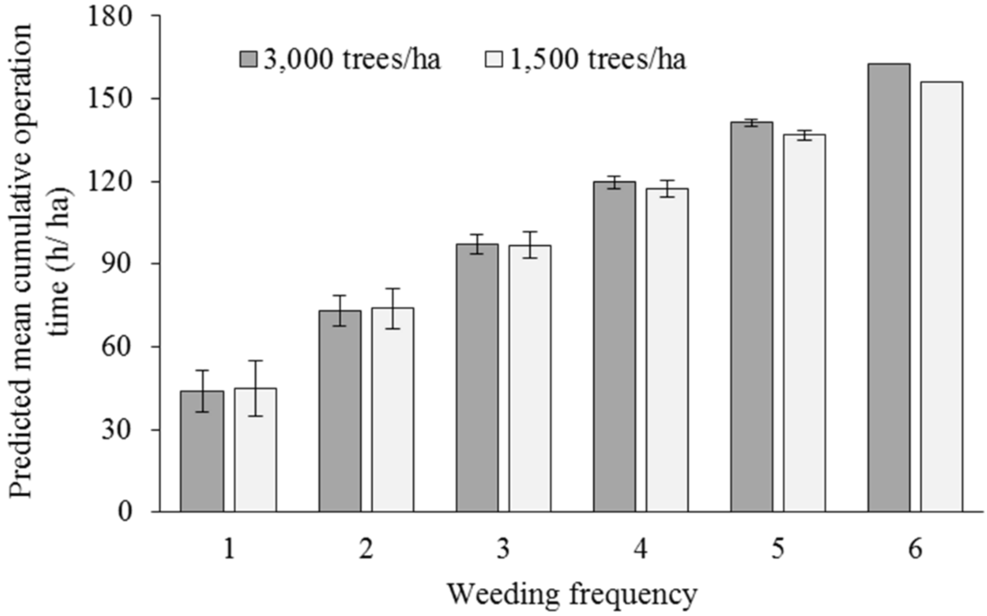

Figure 4.2. The predicted cumulative operation time for different weeding frequency under different initial planting density.

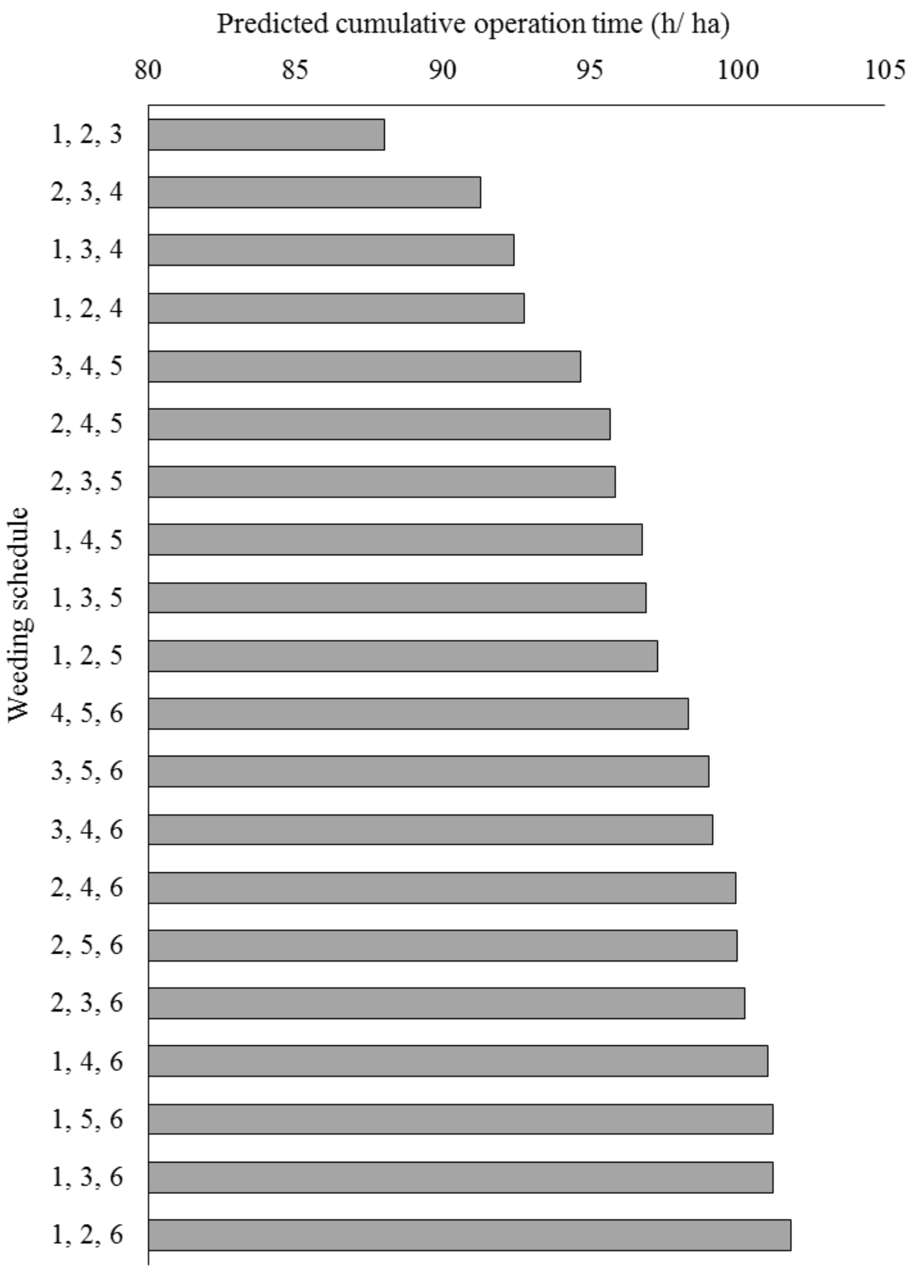

Figure 4.3. Predicted operation time under different weeding schedules for three-times weeding frequencies.

4.4. Discussion

Weeding operation time was affected by *WH* and *WHH* (Table 4.2). Given that the coefficients of *WH* and *WHH* were positive, the higher the weeds or the higher the weed height relative to sugi height required a longer operation time. The present results confirm the finding by Kinjou et al. (2011b) suggesting that weed height and the ease of recognition of the planted trees affect the weeding operation time. Thus, we conclude that keeping the weed height low is important to reduce the weeding operation time. However, even if the weed height is low, a longer operation time is required if the planted tree height is low; therefore, the planted tree height as well as the weed height is important for reduction of the weeding operation time. The result suggests that the operation time decreases year after year if the weed height is constant, because of the annual tree growth of planted trees.

Initial planting density also positively affected weeding operation time (Table 4.2). One possible reason why initial planting density affects operation time is that operators have to circumvent more planted trees when the planting density is higher. Recent studies indicate that low-density planting is effective with regard to reduction of the initial planting cost (Sasaki et al. 2009; Ota et al. 2013) and planted tree growth (e.g. Fukuchi et al. 2011). The present results suggest that reducing the initial planting density promotes reduction of weeding operation time, thus we conclude that low-density planting is also effective for reduction of weeding operation time. However, it should be noted that the reduction in weeding time achieved with low-density planting is much smaller than that attained by reduction of weeding frequency (Figure 4.2).

Cumulative operation time decreased approximately 6% for each one-treatment reduction in weeding frequency. Even if the weeding frequency was halved, the cumulative operation time was not similarly halved (Figure 4.2). When weeding is not conducted in a given year, the operation time for that year is zero. Thus, the cumulative operation time decreased with the reduction of weeding frequency. However, the operation time of weeding is increased in the year immediately following that when weeding is not conducted. This is because *WH* and *WHH* increase in the absence of weeding, and have positive effects on the subsequent weeding operation time. Thus, the cumulative operation time does not decline commensurate with the decrease in weeding frequency. Both the operation time reduction due to non-weeding in a given year and the increase in operation time resulting from growth of *WH* and *WHH* must be considered. With a three-treatment weeding frequency, the cumulative operation time tended to increase when weeding was not conducted in consecutive years (e.g. treatment in years 1, 2, and 6, or years 1, 3, and 6, or years 1, 5, and 6) (Figure 4.3). We thus conclude that weeding should be conducted in consecutive years to reduce weeding cost.

This study clarified the factors that affect weeding operation time. We conclude that weeding schedules as well as weeding frequency affect the weeding operation time. With regard to weeding operation time, we recommend that weeding is conducted in consecutive years. It should be noted that this study only focused on the weeding operation time. Fukumoto et al. (2017) showed that weeding frequency as well as weeding schedule affects the growth of planted trees. Kobe et al. (1995) also indicated that tree mortality is affected by weeding treatment. We expect that the optimal weeding frequency and schedule will be determined by considering not only the cost (i.e. weeding operation time), but also the growth and mortality of planted trees. Thus, additional studies accounting for weeding operation time, growth of planted trees, and planted tree mortality are required. We also have to consider the effect of weeding frequency reduction on total management cost and stand volume for sustainable forest management.

Chapter 5. The relationship between sugi height growth and weeding operation time: Assessment of optimal weeding schedules using Monte Carlo method.

5.1. Introduction

The reduction of weeding cost has become important subjects in Japan. Weeding cost can be reduced in principal when weeding is not conducted or when weeding frequency is shortened; however, planted trees growth may be adversely suppressed due to competition with weeds. Therefore, the tendency of negative trend of planted trees growth should be put into consideration when conducting assessment of weeding cost reduction. Some researchers reported about planted trees growth under non-weeding treatment (Hirata et al. 2012, Fukumoto et al. 2015), three-times treatment (Watanabe et al. 2013; Fukumoto et al. 2015a) and various weeding frequency treatment (Kinjou et al. 2011a). For example, Kinjou et al. (2011) showed that sugi height and diameter is decreased as weeding frequency decreases. Hirata et al. (2012) reported that the planted trees height and diameter growth was affected by vertical weed suppressions in non-weeding hinoki stand. As stated above, several researcher reported about the relationship between weeding frequency reducing and planted trees growth. However, our previous chapter suggested that the sugi height growth is depending not only on weeding frequency but also on weeding schedule. Therefore, we have to clarify the effect of both weeding frequency and schedule on planted trees growth.

Weeding schedules affect not only on planted trees growth, but also on weeding operation time (Watanabe et al. 2013, Fukumoto et al. 2017). For example, Watanabe et al. (2013) reported that cost for weeding conducted for 3 times in years 2, 4 and 6 after planting could reduce approximately only 30 % in comparison with the cost for 6 times of annual weeding treatment. This result indicated that weeding cost is not necessarily proportional to weeding frequency.

Although the importance of weeding schedule for decision of optimum weeding schedules is clarified in the previous chapters, there is no study that discusses the optimum weeding schedules in terms of sugi height and weeding operation time. Therefore, to decide the optimum weeding schedules, it is necessary to clarify the relationship between sugi height and operation time. The main objectives in this chapter are to clarify the relationship between sugi height growth and weeding operation time, and then to propose optimal weeding schedules by applying Monte Charlo method.

5.2. Materials and Methods

Data collection

We applied field measurements data, which were obtained from our study site. The data included the sugi mean height (m), weed mean height (m) and weeding operation time per one time (h/ha) for a 6 year-period after planting in each blocks (Table 4.1). The description of field measurements method and data described chapter 3 (sugi and weed height) and 4 (weeding operation time).

Statistical model

We assumed that the observed mean annual sugi and weed height growth with a normal distribution, as follows:

$$G^c \sim \text{Normal}\ [\ln(\bar{G}^c), 0.02] \qquad (5\text{-}1)$$

$$G^w \sim \text{Normal}\ [\ln(\bar{G}^w), 0.16] \qquad (5\text{-}2)$$

$$T \sim \text{Normal}[\ln(\bar{T}), 6.81] \qquad (5\text{-}3)$$

where G is the observed mean annual height growth of sugi or weeds (m year^{-1}), $\bar{G}$ is the expected mean annual height growth (m year^{-1}) of sugi or weeds, and T is the observed operation time per weeding treatment per hectare (h/ha), $\bar{T}$ is the expected operation time (h/ha). 0.02, 0.16 and 6.81 indicates the variances. The statistical models are summarized in the chapters 3 and 4. The expected mean annual height growth and the expected operation time per one time as follows;

$$\ln(\bar{G}^{c}) = -0.22 - 0.15WH + 0.12H - 0.65WHH - 0.11S \qquad (5\text{-}4)$$

$$\ln(\bar{G}^{w}) = 0.38 - 0.09H - 0.43WHH - 0.30S \qquad (5\text{-}5)$$

$$\ln(\bar{T}) = 2.8310 + 0.1740WH + 0.2056WHH + 0.0001D \qquad (5\text{-}6)$$

where $\bar{G}^{c}$ is expected mean annual sugi height growth (m/ year), $\bar{G}^{w}$ (m/ year) is expected mean annual weed height growth (m/ year) and $\bar{T}$ is expected operation time per one time (h/ ha). The explanatory variables includes the mean sugi height prior growing seasons(H) (m), weed height just after weeding operation (WH) (m), relative height weed to sugi (*WHH*), slope aspect (S) and tree initial planting density (D) (trees/ ha). Then, WHH was expressed as WH divide by H. In the case of slope aspects, we defined S as 1 when the plot faced south, otherwise 0.

Data analysis

To clarify the relationship between sugi mean height and weeding operation time, we simulated 6-years old sugi height and cumulative weeding operation time under different weeding frequencies and schedules. In total, we simulated 64 weeding schedules. Mean annual height growths and operation time per one time were randomly generated from equation (5-4), (5-5) and (5-6). Then, we repeated 100 times sugi height and weeding operation time under 64 schedules according to Monte Carlo analysis. We assumed that initial sugi height and initial weed height were 0.6 m and 0 m, respectively. We also assumed that slope aspect and initial planting density were north-facing and 3,000 (tree /ha), respectively.

We focused on three times weeding frequency for deciding optimum weeding schedules. We classified weeding schedules into three groups from (A, B, C) using multiple comparisons test in terms of 6-years old sugi height and cumulative operation time. Group A is classified as the schedules under which the highest mean sugi height or the shortest operation time are achieved. Group C is the schedules resulting in the lowest sugi height or the longest operation time. Group B is between group A and C.

5.3. Results

The relationship between sugi height and cumulative operation time

There is positive correlation between sugi mean height and mean cumulative operation time (r = 0.94, $p<0.05$) (Figure 5.1). Mean cumulative operation time increased by approximately 28 (h/ ha) with one-treatment increases in weeding frequency. Sugi mean height was occasionally approximately the same under different weeding frequency. Mean height of sugi and mean cumulative operation time were different under the same weeding frequency.

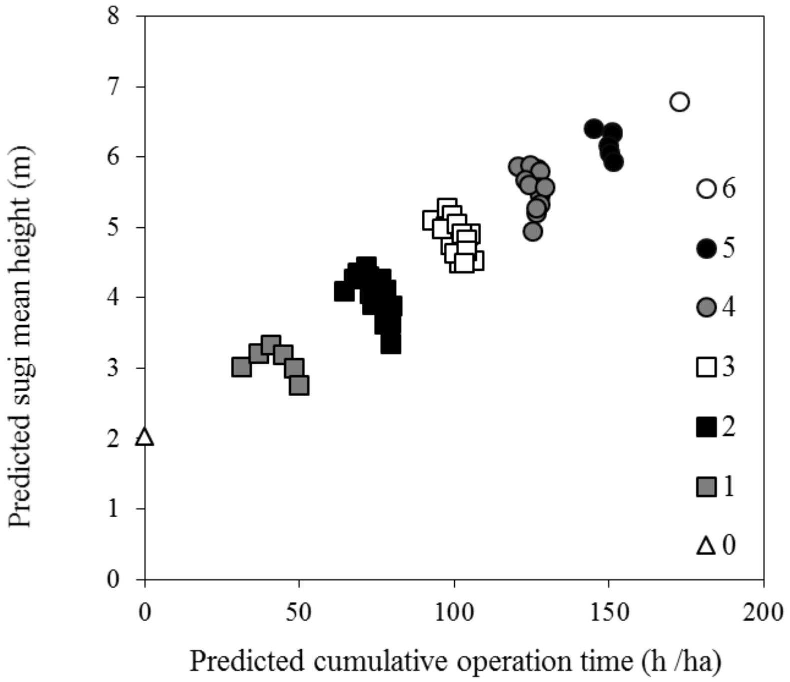

Figure 5.1. The relationship between predicted sugi mean height (m) and predicted cumulative operation time (h/ ha) under different weeding schedules. The numbers indicate the weeding frequencies.

Assessment of optimal weeding schedules under three times weeding frequencies

The highest mean height of sugi, 5.3 m is observed in weeing treatment in years 1, 2 and 4 while the lowest mean height, 4.2 m is observed in years 4, 5 and 6. Again, weeding treatment in years 2, 5 and 6 required the longest operation time, 106 (h/ha) whereas weeding treatment in year 1, 2 and 3 required the shortest operation time of 92 (h/ha). In the case of predicted mean sugi height, the weeding treatment in years (1, 2 and 4), (1, 3 and 5,), (1, 2 and 5), (1, 2 and 3), (2, 3 and 5), (1, 3 and 4) were classified as group A, based on multiple comparisons test (Table 5.1), whereas weeding treatment in years (4, 5 and 6) was classified as group C. Similarly, the weeding treatment in years (1, 2 and 3), (2, 3 and 4), (1, 3 and 4), (1, 2 and 4) were classified as group A in terms of mean cumulative operation time. The weeding treatment in years (2, 5, 6), (1, 3, 6), (1, 2 and 6), (3, 4 and 6), (2, 4 and 6), (2, 3 and 6), (3, 5 and 6), (1, 4 and 6), (2, 4 and 5) were classified as group C.

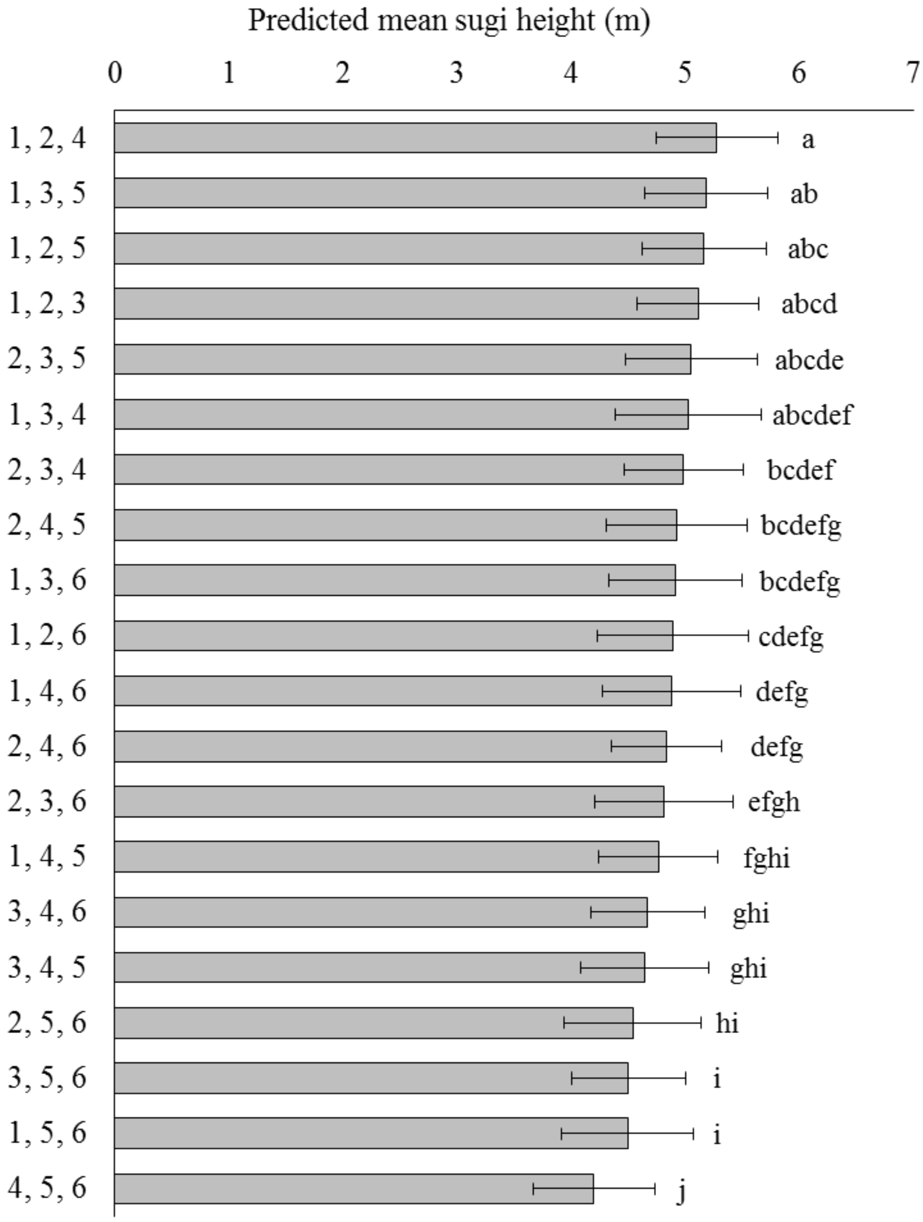

Figure 5.2. Predicted mean sugi height different weeding schedules under three times weeding frequency. Error bar indicate standard deviations.

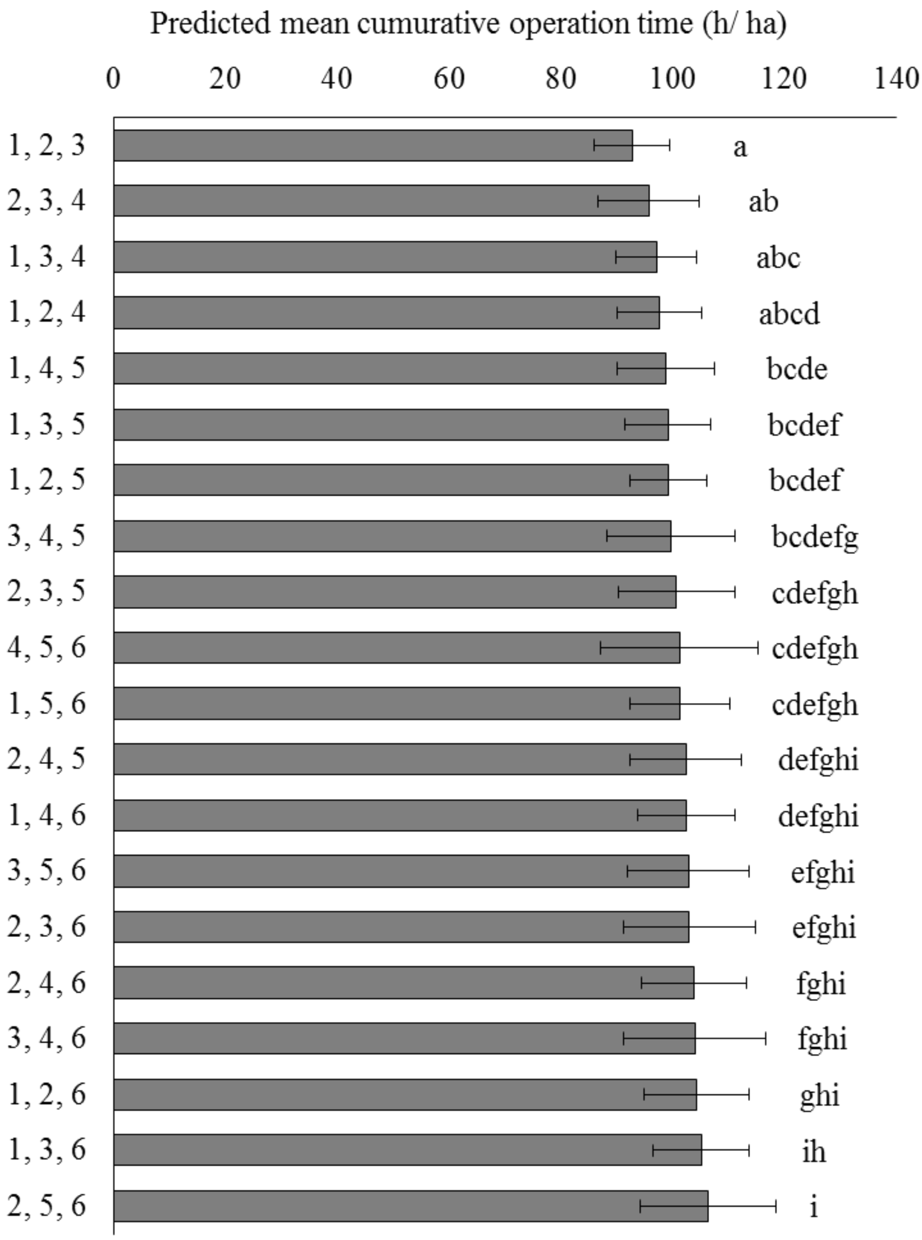

Figure 5.3. Predicted mean weeding operation time different weeding schedules under three times weeding frequency. Error bar indicate standard deviations.

Table 5.1. The weeding schedules classified three groups in terms of predicted mean sugi height and predicted mean cumulative operation time, based on multiple comparison test ($p < 0.05$).

Group	Weeding schedules			
	Mean sugi height		Mean cumulative operation time	
A	1,2,4	1,3,5	1,2,3	2,3,4
	1,2,5	1,2,3	1,3,4	1,2,4
	2,3,5	1,3,4		
B	2,3,4	2,4,5	1,5,6	4,5,6
	1,3,6	1,2,6	2,3,5	3,4,5
	1,4,6	2,4,6	1,2,5	1,3,5
	2,3,6	1,4,5	1,4,5	
	3,4,6	3,4,5		
	2,5,6	3,5,6		
	1,5,6			
C	4,5,6		2,5,6	1,3,6
			1,2,6	3,4,6
			2,4,6	2,3,6
			3,5,6	1,4,6
			2,4,5	

5.4. Discussion

The relationship between sugi mean height and mean cumulative operation time has positive correlation (*r*= 0.94) (Figure 5.1). This result implied that sugi height grows as weeding operation time increases. Sugi mean height can be approximately the same between applying different weeding frequencies (Figure 5.1). This result suggests that even though weeding frequencies reduced, sugi height can grow similarly depending on weeding schedules. Therefore, it will be wise to consider not only weeding frequency but also weeding schedules for reducing weeding cost. In the case of mean weeding operation time, weeding frequency increased by approximately 28 (h/ ha) with increasing weeding frequency. Mean operation time was not same when weeding frequencies were different. This result shows that weeding operation time is affected by weeding frequency. However, the weeding operation time depends on weeding schedules; therefore, it will be able to reduce weeding operation time based on setting of not only weeding frequency but also weeding schedules.

The weeding treatment in years 1, 2 and 4 achieved the highest sugi height, whereas the treatment in years 4, 5 and 6 years resulted in the lowest sugi height (Figure 5.2). Mason (2006) based on investigating the interaction between competition grasses and juvenile radiate pine in New Zealand, indicated that the competition control was the most critical during the first year. Similarly, Wagner et al. (1996) examined the six patterns of vegetation control schedules in Canada, and they suggested that vegetation control immediately after planting was the most important for coniferous species. Our simulation results also pointed that the sugi height under the weeding conducted after planting 1 or 2 years is higher than that of any other schedules. Therefore, weeding operation at an initial stage of plantation is important in terms of sugi height growth.

Weeding operation time is the longest when weeding is conducted in years 2, 5 and 6, while the operation time is the shortest weeding treatment in years 1, 2 and 3. More weeding operation time is required when weeding is not conducted on consecutive years. This implies that the amount of weeds influences weeding operation time; when weeding is not conducted in a given years, the amount of weed increases accordingly.

Therefore, weeding operation time is more required when weeding is not conducted on consecutive years under same weeding frequency. This result suggests that weeding operation on consecutive years is important for reducing weeding operation time.

Weeding treatment in years (1, 2 and 3), (1, 2 and 4), (1, 3 and 4) were classified as group A for both sugi height and weeding operation time in accord with the results of multiple comparison test (Table 5. 1). Therefore, these schedules are optimum weeding schedules. The schedules, which were classified group C, showed lower sugi height with more weeding operation time. It is recommended to avoid those weeding schedules. The previous study reported that weeding cost could be reduced approximately 30 % when weeding is conducted in years 2, 4 and 6 (Watanabe et al. 2013). From our results, weeding treatment in years 2, 4 and 6 was classified as group B in the case of sugi mean height. Therefore, from the point of view sugi mean height, this schedule may become optimum weeding schedules. However, the schedule was classified as group C in the case of weeding operation time. These results showed that the schedule may not be optimum weeding schedule for our study site, and the schedule effectiveness is depending on the situation such as competition weed type. Therefore, the competition weed type of the sites will be also necessary to consider optimum weeding schedules.

It should be noted that our results cannot be applied to other whole regions because optimum weeding schedules depend on each regional condition. Therefore, we have to construct statistical models that can be considering various conditions. Some studies reported that the weed structure and amount affected planted trees growth and operation time (Kinjou et al. 2011b, Hirata et al. 2012, Kitahara et al. 2013, Yamagawa et al. 2016). By constructing statistical models that focus on weed character, it will be possible to examine optimum weeding schedules with regional conditions. In this study, clarification is made for optimum weeding schedules using measurements data 6 years after planting. An effect of weeding reduction on stand volume and total operation cost will be clarified in future studies.

Chapter 6. The effects of competition between sugi and weed on both subsequent growth.

6.1. Introduction

Recently, reducing weeding cost is important subjects in Japan. Generally, weeding completion criteria defines duration after planting; for example, weeding is completed three to six years after planting in Japan. However, we should construct flexible weeding completion criterion that considers the competition between planted trees and weeds, which may be different among regions.

Several researchers reported the competition between planted trees and weed (Tanimoto 1982; Tange et al. 1993; Hirata et al. 2012; Tsurusaki et al. 2016; Yamagawa et al. 2016). For example, Yamagawa et al. (2016) examined the competition between sugi and weed at the individual tree level, and they indicated that sugi height decreased when sugi was completely covered by weed. Thus, one completion criteria is whether weed reach planted tree height after finishing weeding. Therefore, weeding completion criteria should not overtake sugi height to weed height for keeping sugi growth.

Some researchers defined weeding completion criteria (Ogata and Nagatomo 1971; Tsurusaki et al. 2016; Yamagawa et al. 2016). Ogata and Nagatomo (1971) investigated the competition between sugi and Japanese plume-grass (*Miscanthus sinensis*), and they suggested that weeding treatment could be completed when sugi height reached at 1.5 m, on the other hand, Sakura (1987) showed that sugi height 2.0 m might become weeding completion criteria. One limitation of previous studies is that they did not consider the weed growth after finishing weeding. Thus, weed may reach planted tree height even if the criteria developed by previous studies were applied. Yamagawa et al. (2016) investigated the effect of competition between sugi and weed on sugi height growth, and suggested that planted trees height and the relative height of weed to planted trees are available indices for judgements of weeding necessity. This study indicated that the weeding completion criteria might also need to consider both planted trees height and relative height of weed to planted trees. However, the effect of relative height of weed to sugi on subsequent growth of sugi and weed after finishing weeding has not been clarified. Therefore, to examine the weeding completion criteria under which weed does not overtop sugi height over time, we also should consider the effect of relative height of weed to sugi on height growth of sugi and weed.

The main objective in this chapter is to establish the weeding completion criteria. To achieve this objective, we simulated sugi and weed height after weeding completely applying previous weeding completion criteria (e.g. Ogata and Nagatomo 1971; Sakura 1987). Also, we clarified the effect of relationship between sugi height and relative height of weed to sugi on subsequent both growth.

6.2. Materials and Methods

Data collection and statistical model

We used the field measurement data of sugi and weed height. The summary of data were described in the chapters 3 and 5. Also we used two statistical models which calculated sugi and weed annual height growth models. The models constructed by chapter 3, as follows;

$$\ln(\bar{G}^c) = -0.22 - 0.15WH + 0.12H - 0.65WHH - 0.11S \qquad (6\text{-}1)$$

$$\ln(\bar{G}^w) = 0.38 - 0.09H - 0.43WHH - 0.30S \qquad (6\text{-}2)$$

where $\bar{G}^c$ is expected mean annual sugi height growth (m/ year), $\bar{G}^w$ (m/ year) is expected mean annual weed height growth (m/ year). The explanatory variables indicates the sugi mean height prior growing seasons (*H*), weed height just after weeding treatment (*WH*), the relative height weed to sugi (*WHH*), and slope aspect (*S*). The description these growth models refer to chapter 3.

Data analysis

First, assuming that weeding is completed when sugi height reached 1.5 m and 2.0 m referring to the previous weeding completion criterion (e.g. Ogata and Nagatomo 1971; Sakura 1987), we simulated sugi and weed height for seven-years after planting. Next, we simulated height growth of sugi and weed for 5 years after weeding operation completion under different settings of two criteria for weeding operation completion; sugi height (*H*) and *WHH* values, which is calculated *WH* divided by *H*. We tested a total of 22 combinations of two different *H* values (1.5 m and 2.0 m) and 11 *WHH* values from 0 to 1.0 with interval of 0.1. All simulation assumed only north-facing slope, because both slopes showed same trends.

6.3. Results

If we applied the previous weeding completion criteria, how does sugi and weed height grow for seven-years?

Weed height reached sugi height seven years after planting when weeding was completed after sugi height reached 1.5 m. On the other hand, weed height did not overtop sugi height for seven years when weeding was completed after sugi height reached 2.0 m.

(a) Weeding is completed when sugi reached 1.5m (b) Weeding is completed when sugi reached 2.0 m

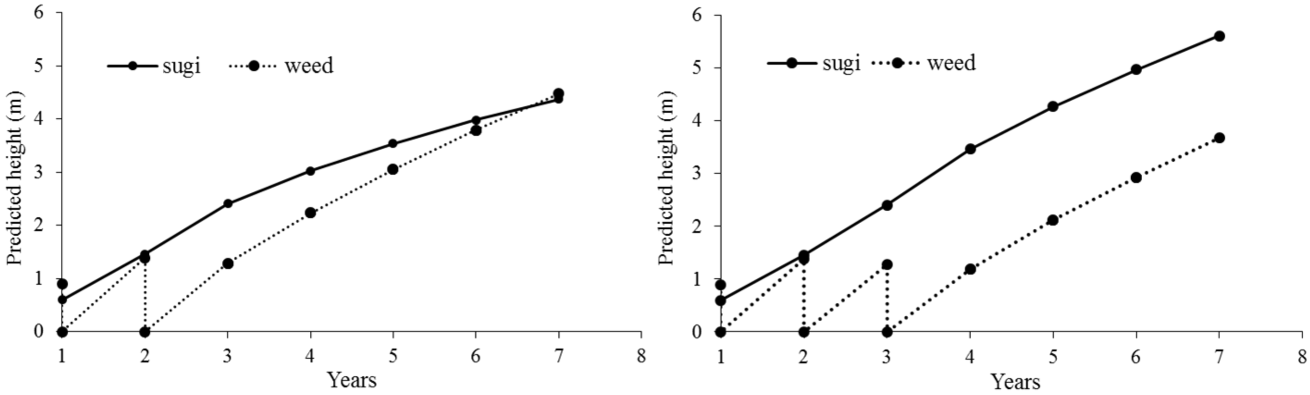

Figure 6.1.Predicted sugi and weed height for seven-years when applying previous weeding completion criterion.

How should we keep weed height not to cover weed with sugi when we judge the necessity of weeding treatment?

The sugi was covered by weed completely when *WHH* values was more than 0 under sugi height 1.5 m (Figure 6.2. (a)). In the case of sugi height 2.0 m, sugi was covered with weed five years later when *WHH* values were more than 0.3 (Figure 6.2. (b)). Weed height overtopped sugi height at early stage when *WHH* values increased.

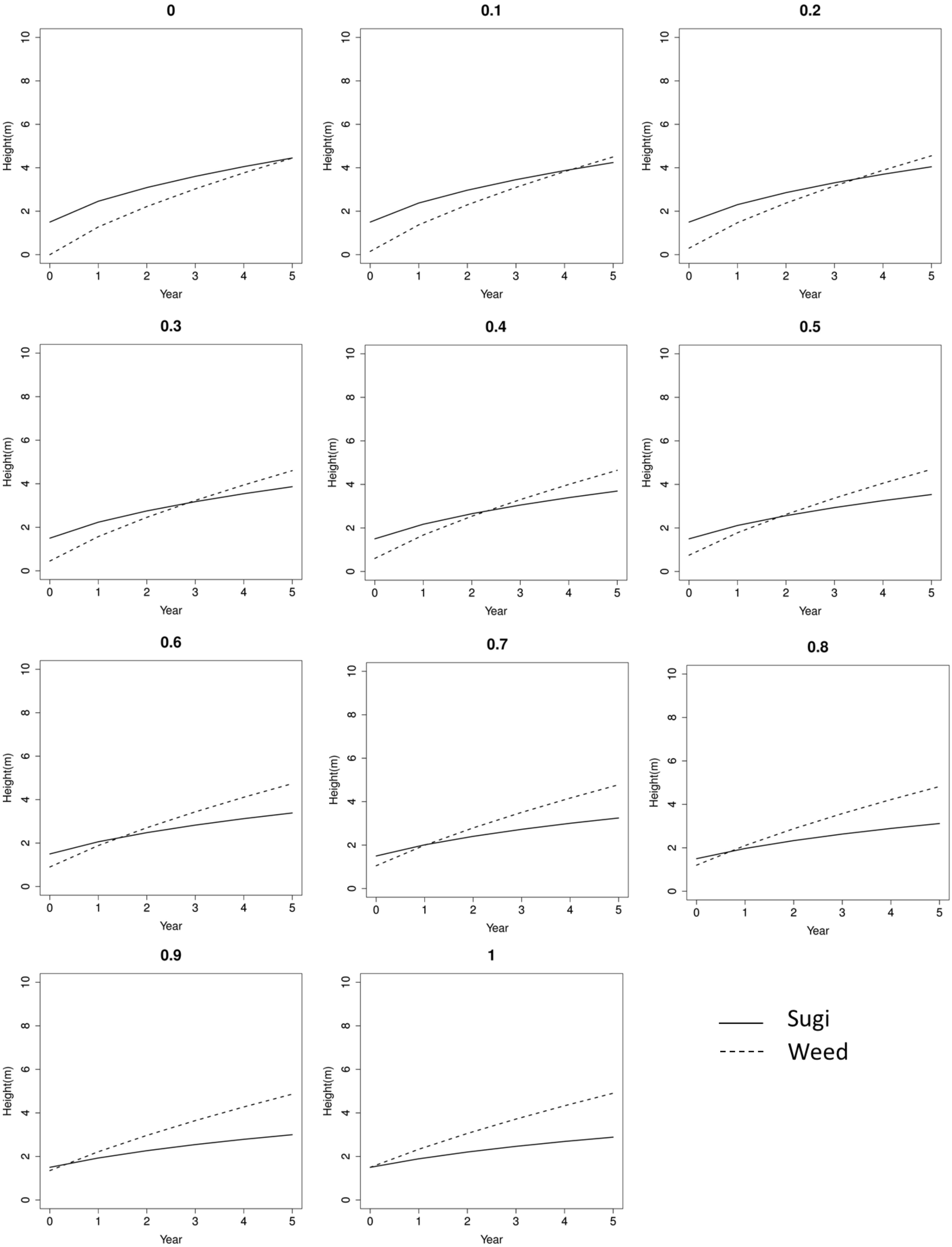

Figure 6.2. (a). The effect of sugi height and *WHH* on subsequent sugi and weed height growth in the case of sugi height 1.5 m. Each graph title indicates WHH values.

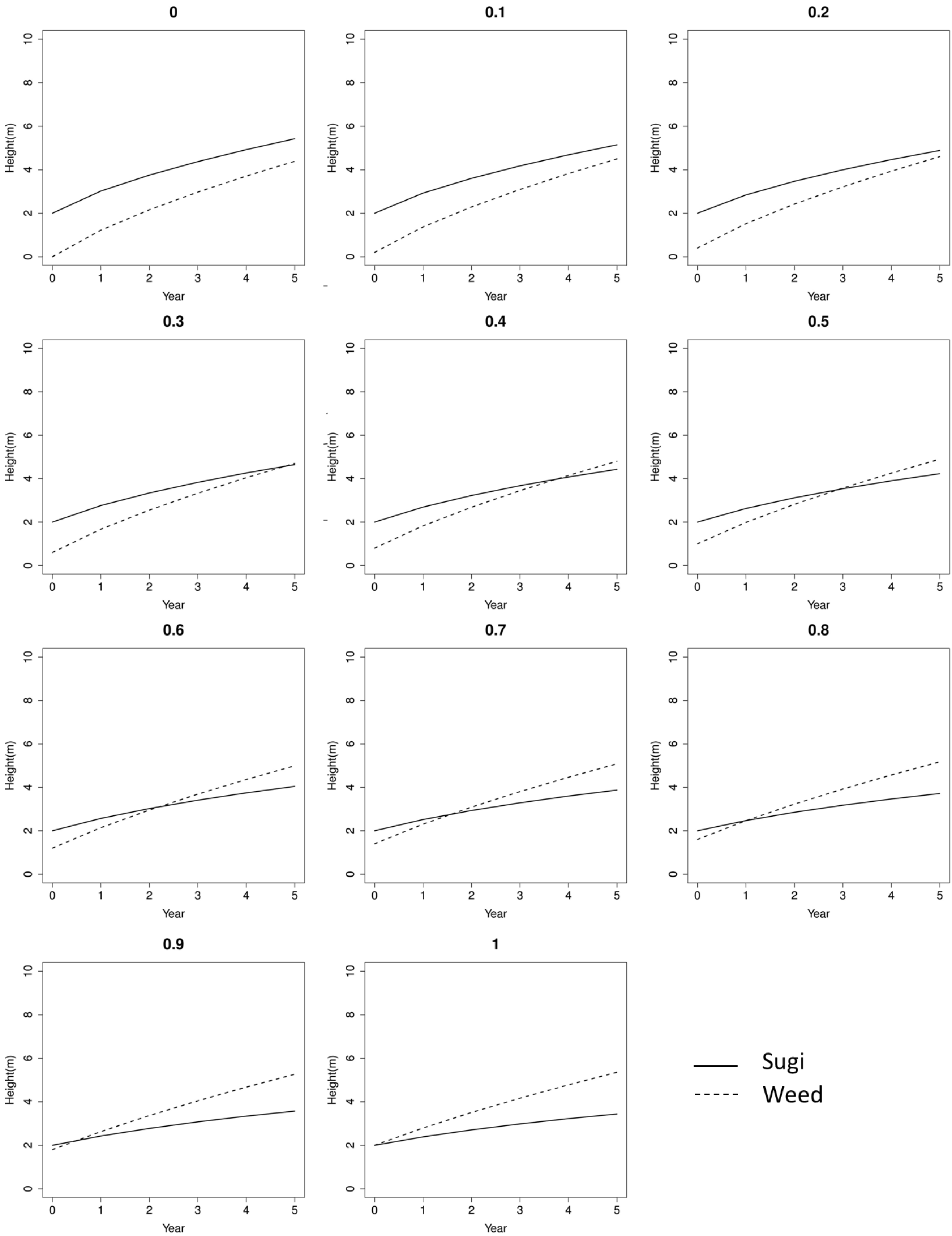

Figure 6.2. (b). The effect of sugi height and *WHH* on subsequent sugi and weed height growth in the case of sugi height 2.0 m. Each graph title indicates *WHH* values.

6.4. Discussion

The sugi height was needed at least 1.5 m not to be covered by weed within 7 years. (Figure 6.1(a)). However, noted that weed and sugi height might become approximately same height five years later when sugi height was 1.5 m. Yamagawa et al. (2016) suggested that small sugi trees were strongly affected by weed suppressions in comparison of large one. Therefore, if we finished weeding treatment when sugi height is approximately 1.5 m, we may need to conduct improvement cutting in early stage. Sugi height growth decreased when the top of sugi was covered by weed completely (Tsurusaki et al. 2016, Yamagawa et al. 2016). Therefore, sugi height should be 2.0 m to avoid the decrease of sugi growth. These results suggest that sugi height 2.0 m may be one criterion which decides weeding completion.

Assuming that sugi 2.0 m height is weeding completion criteria, weed did not overtop sugi 7 years later unless *WHH* was less than or equal to 0.3 (Figure 6.2 (b)). Thus, sugi height 2.0 m and *WHH* values no more than 0.3 may become one weeding completion criteria. Moreover, weed may overtop sugi height using some previous weeding completion criteria (e.g. Ogata and Nagatomo 1971). Therefore, it is important to consider for the effect of competition between planted trees and weed on subsequent planted trees growth.

This chapter clarified the effect of sugi and weed height growth on subsequent both growth under different sugi height and the relative height weed to sugi. However, our statistical model estimates annual sugi and weed height growth, but we could not consider the both height growth for different growing seasons. Yamagawa et al. (2016) indicated that we should take into account sugi and weed growing seasons for judgement of weeding completion. Therefore, we have to construct statistical model which can consider planted trees and weed growing seasons. Also, sugi height growth differed with the different weed type (Kitahara et al. 2011; Tsurusaki et al. 2016). Therefore, we also should consider weeding completion criteria for each weed type.

Chapter 7. General Discussion

This study investigated the optimum weeding schedules in terms of sugi survival rate, sugi height growth and weeding operation time. First, we simulated the sugi mortality, accidental cutting and survival rate using statistical models (see Chapter 2). Based on the simulation results, we conclude that weeding frequency should be more than one time in terms of sugi survival rate. The field data suggested that sugi survival rate including mortality and accidental cutting rate decreased when weeding were not conducted 2 years after planting. This result indicates that we need to conduct weeding after planting immediately for reducing mortality and accidental cutting.

In chapter 3, we constructed sugi and weed annual height growth models and simulated sugi height under different weeding frequency and schedules. The simulation results showed the sugi height decreased approximately 20 % by weeding frequency reducing one time (Figure 3.1). Some researchers indicated that the weeding conducted immediately after planting was important for coniferous tree species growth (e.g. Wagner et al. 1996, Mason et al. 2006). Our results showed also same tendency of these studies (Figure 3.2); therefore, it is important that weeding is conducted immediately after planting for planted trees growth.

In chapter 4, we focused on weeding operation time under different weeding frequency and schedules. The simulation results showed that weeding operation time decreased approximately 6 % with one-time weeding frequency decreases. The consecutive weeding schedules tended to decrease weeding operation time, whereas weeing schedules that were not consecutive required weeding operation time. These results suggests that consecutive weeding schedules can reduce weeing operation time.

Based on the results of chapter 3 and 4, we assessed optimum weeding schedules that balance sugi height growth with reducing weeding operation time in chapter 5. We used Monte Charlo method and multiple comparison analysis. This results indicated that the optimum weeding schedules on our study site were weeding conducted in years (1, 2 and 3), (1, 2 and 4), (1, 3 and 4) (Table 5.2). These schedules implies that the weeding conducted consecutively and immediately after planting may become optimum weeing schedules.

Also we examined when we could complete weeding operation in chapter 6. When weeding was completed after sugi height reaches 2.0 m, weed may not overtop sugi in the five years later. Therefore, sugi height 2.0 m may become weeding completion criteria. In addition, weed overtopped sugi when *WHH* value was more than 0.3. Therefore, we recommend that weeding is completed with sugi height 2.0 m and *WHH* values are not more than 0.3.

In conclusion, weeding conducted immediately and continuously after planting is optimum weeding schedules (e.g. weeding conducted in years 1, 2 and 3 or 1, 2 and 4 or 1, 3 and 4) for reducing weeding cost. We also conclude that sugi height 2.0 m and *WHH* value of no more than 0.3 may become the one of weeding completion criteria.

Future study

Our study examined the optimum weeding schedules in terms of sugi survival rate, sugi height growth and weeding operation time. However, our optimum weeding schedules and weeding completion criteria may not be applicable other regions. The results of our study depending on slope aspects and initial planting density. For example, sugi and weed growth were affected by slope aspect, and weeding operation time was affected by initial tree densities. These results suggest that optimum weeding schedules depending on each of site conditions. Moreover, it is well known that the planted trees growth differed with each weed type (e.g. Kitahara et al. 2011, Tsurusaki et al. 2016, Yamagawa et al. 2016). Thus, we need to construct statistical models which includes weed type and site condition.

Our sugi and weed growth models were developed using data from field measurements for only 6 years after planting. Our statistical model used exponential function, and so the reduction of weed height growth over time was not reflected. Therefore, the predicted weed growth tended to overestimate the observed weed growth. Thus, we may need to get our field measurements continuously and reconstruct statistical models accordingly. Also, we could not clarify sugi trees and weed growth, and total management cost until cutting. We need to clarify how weeding frequency reducing affect sugi growth and total management cost until the final harvesting in future study.

As for weeding completion criteria, there is “free-growing” that considered each planted trees and competition weed in the case of British Colombia, Canada. If we referred these criteria, first we may need to classify regions based on planted trees, weed and regional types. Also, “free-growing” was established in terms of the competition between planted trees with weed within radius 1~2 m. Therefore, we should clarify the effect of competition between planted trees and weed on planted trees growth in individual trees level. If we could consider those things, we can contribute to construct the low cost silviculture system in the future.

Summary

Chapter 1. General Introduction

Weeding is an important role for sustainable forest management. Weeding is conducted to prevent the competition for light, nutrients, and soil water between planted trees and weed. There are various weeding methods in the world. Weeding is usually conducted at least once or twice per year for 5 or 6 years after planting using brush-cutter in Japan. This method result in high cost, accounting 40 % total cost during the first 10 years after planting. Therefore, the reduction of weeding cost is important theme in Japan. However, the optimum weeding schedules in terms of tree survival rate, tree growth and weeding operation cost were not examined. Also, only few studies have focused on weeding completion criteria. Therefore, we examined the optimum weeding schedules and weeding completion criteria on young sugi plantation stand in north-western Japan, towards low-cost silviculture system.

Chapter 2. The effect of weeding frequency on the mortality and accidental cutting of planted sugi trees.

We investigated the effects of weeding frequency, slope aspect and initial tree density on the mortality and accidental cutting of planted sugi in southern Kyushu. To predict the probability of mortality and accidental cutting, we used the multinomial logistic regression model using weeding frequency, slope aspect and initial tree density. The highest mortality on north- and south-facing slopes was found in non-weeding plot (33.3 %) and every-year weeding plot (16.9 %), respectively. Accidental cutting of planted Sugi was found in 3 or 4 times weeding plots. Multinomial logistic regression model showed that mortality was affected by slope aspect and initial tree density. Mortality decreased with the increase of weeding frequency on north -facing slope, while mortality was invariable regardless of weeding frequency on south-facing slope. Accidental cutting rate was invariables regardless of weeding frequency on both slopes. The mortality rate and accidental cutting rate under the 1,500 trees/ha density was higher than that under the 3,000 trees/ ha. These results suggest that weeding frequency should be determined according to slope aspect and initial tree density.

Chapter 3. The effect of weeding frequency and timing on the height growth of young sugi stands.

We investigated the height growth of planted sugi saplings in southwestern Japan. First, we developed stand-level sugi and weed annual height growth models that accounted for tree spacing, slope aspect, and mean sugi height at the end of prior growing season and mean weed height just after weeding. Then, we simulated sugi heights after the sixth growing season under 64 different weeding schedules, using the developed model to examine the effects of the weeding frequency and the timing of weeding. The selected model for sugi height growth was expressed in terms of mean sugi height, mean weed height, slope aspect, and the relative height of weeds to sugi. In the case of weeds, the selected model was expressed in terms of mean sugi height, slope aspect, and the relative height of weeds to sugi. The simulation showed that sugi height decreased approximately 20 % for every one-time reduction in the number of weeding. The simulation also showed that earlier, rather than later, weeding yielded better sugi growth. In conclusion, not only weeding frequency but also weeding schedules are important for sugi height growth.

Chapter 4. The effect of weeding frequency and timing on weeding operation time.

We investigated the effect of weeding frequency and weeding schedules on weeding operation time in a sugi plantation stand. We developed a weeding operation time model that accounts for sugi height, weed height, relative height of weeds to sugi, slope aspect and initial planting density. We simulated the cumulative weeding operation time after six growing seasons using the selected model. The best model for weeding operation time was expressed in terms of weed height, relative height of weeds to sugi and initial planting density. The simulation indicated that weeding operation time decreased approximately 6% for each one-treatment decrease in weeding frequency. Under a three-treatment weeding frequency scenario, the simulated cumulative operation time when weeding was conducted during non-consecutive years was longer than that when weeding was conducted during three consecutive years. Thus, the results suggest that carrying out weeding treatment during consecutive years is the more effective for reduction of weeding costs. We conclude that weeding schedule as well as weeding frequency must be considered for reduction of weeding operation time.

Chapter 5. The relationship between sugi height growth and weeding operation time: Assessment of optimal weeding schedules using Monte Carlo method.

We examined the relationship between sugi mean height and cumulative weeding operation time. Then, we considered the optimum weeding schedule so that the sugi growth is larger and weeding operation time is shorter. We estimated the 6 years old sugi height and cumulative weeding operation time under all weeding schedules using the predicted models constructed by chapter 3 and 4. Then we focused on 3 time weeding frequency (i.e. 20 schedules), we examined the optimum weeding schedule using multiple comparison test. There were the positive correlation between sugi height and cumulative operation time (r =0.94, p <0.05), and the cumulative weeding operation time decreased 28 (h/ha) with decreasing weeding frequency. Even if the number of weeding frequency differed, the sugi height had the almost same in some cases. The multiple comparison result showed that weeding conducted immediately and consecutively after planting is optimum weeding schedules (weeding conducted in years 1, 2, and 3, or 1,2, and 4, or 1, 3, and 4).

Chapter 6. The effects of competition between sugi and weed on both subsequent growth.

We investigated the effect of competition between sugi and weed on subsequent both growth. Then, we examined the weeding completion criteria in terms of subsequent sugi and weed growth after weeding is finished. First, we simulated the sugi and weed growth by applying conventional criteria using both sugi and weed height growth models constructed by chapter 3 and 4. Then, we examined the effect of different relative height of weed to sugi (*WHH*) and initial sugi height on subsequent height growth of sugi and weed. When we applied the one conventional criteria, that is, the weeding is completed when sugi height reaches 1.5 m, weed height overtopped sugi height. In contrast, when we applied another conventional criteria that sugi height reaches 2.0 m, weed did not overtop sugi height. Thus, sugi height should reach 2.0 m when weeding is completed. Also, in the case of the height 2.0 m-height criteria, sugi was overtopped by weed when *WHH* value was over 0.3. These results suggest that sugi height 2.0 m and *WHH* values more less than 0.3 should be used as the one of weeding completion criteria.

Chapter 7. General Discussion

Our study examined the optimum weeding schedules in terms of sugi survival rate, sugi height growth and weeding operation time. Also, we examined the weeding completion criteria in terms of subsequent sugi and weed growth after weeding is finished. We concluded that the optimum weeding schedules is weeding conducted immediately and consecutively after planting (i.e. weeding conducted in years 1, 2 and 3, or 1, 2 and 4 or 1, 3 and 4). Also, we concluded that sugi height 2.0 m and *WHH* values less than 0.3 is one weeding completion criteria.

Summary (Japanese)

低コスト育林技術体系確立のための下刈りスケジュールの検討

下刈りは持続可能な森林経営のために重要な作業である。下刈りは雑草木との光，養分，水分の競争を緩和し，植栽木の成長を促す作業で，世界には様々な方法がある。日本では，下刈りは一般的に刈り払い機を用い，年 1～2 回，5～6 年間継続して実施される。刈り払い機を用いた下刈りは，繰り返し実施する必要があるため高いコストがかかっており，植栽後 10 年間の初期保育にかかるコストのうち約 40%を占めている。そのため，下刈り作業コストの削減が重要な課題となっている。これまでに下刈り回数削減について検討されてきたが，植栽木の生存率が高く，植栽木の成長がよいなおかつ下刈り作業時間の短い最適な下刈りスケジュールを検討した事例はない。また，下刈りコスト削減に向けた下刈り終了基準は未だ明確ではない。そこで，本論では，スギ幼齢林における最適な下刈りスケジュールおよび下刈り終了基準を検討した。

Chapter 2. The effect of weeding frequency on the mortality and accidental cutting of planted sugi trees.

（下刈り回数がスギ植栽木の枯死および誤伐に与える影響）

第 2 章では，下刈り回数や斜面方位，植栽密度が植栽木の枯死および誤伐がスギ植栽木に与える影響を検討した。下刈り回数，斜面方位，植栽密度の違いによる枯死および誤伐の発生確率を推定するために多項ロジスティック回帰分析を行った。現地データにおいて，最も枯死率が高かったのは北向き斜面では無下刈り区（33.3%），南向き斜面では毎年下刈り区（16.9%）であった。誤伐はいずれの斜面においても下刈り回数が 3 回，4 回の場合に見受けられた。多項ロジスティック回帰分析の結果，植栽木の枯死は斜面方位および植栽密度に影響を受けることが分かった。北向き斜面では，下刈り回数が増えるほど枯死率は低下したが，南向き斜面では下刈り回数によらず一定であった。誤伐はいずれの斜面においても下刈り回数によらず一定で生じる可能性があった。枯死および誤伐ともに植栽密度が 3,000（本/ ha）と比較して 1,500（本/ha）のときに高くなっていた。これらの結果から，スギの枯死および誤伐の観点から下刈り回数を削減する際には，斜面方位や植栽密度を検討する必要があると考えられた。

Chapter 3. The effect of weeding frequency and timing on the height growth of young sugi stands.

（下刈り回数およびスケジュールがスギの樹高成長に与える影響）

第 3 章では下刈り回数およびスケジュールがスギの樹高成長に与える影響を検討した。まず，変数に植栽密度，斜面方位，期首スギ樹高，期首雑草樹高などを含むスギおよび雑草木の期間成長量を推定する統計モデルを構築した。次に，統計モデルを用い 6 年生時点でのスギ樹高を全下刈りスケジュール別に推定し，下刈り回数やスケジュールがスギ樹高成長に与える影響を検討した。選択されたスギ樹高期間成長量推定モデルは，変数に期首スギ樹高，期首雑草樹高，斜面方位および相対雑草樹高を含んでいた。雑草木樹高期間成長量推定モデルは，期首スギ樹高，斜面方位，相対雑草樹高が変数として含まれていた。両モデルを用いてシミュレーションを行った結果，下刈り回数が 1 回減るたびに約 20%ずつスギの樹高は低くなった。また，植栽後早い段階で下刈りを実施したスケジュールのほうが植栽後遅い段階で下刈りを実施したスケジュールよりもスギの樹高が高くなった。これらの結果から，スギの樹高成長は下刈り回数だけでなく下刈りスケジュールによって左右されると考えられた。

Chapter 4. The effect of weeding frequency and timing on weeding operation time.

（下刈り回数とスケジュールが下刈り作業時間に与える影響）

第 4 章では，下刈り回数とスケジュールが下刈り作業時間に与える影響を検討した。まず，変数に期首スギ樹高，期首雑草樹高，相対雑草樹高，斜面方位，植栽密度を含む 1 回あたりの下刈り作業時間推定モデルを構築した。このとき，選択されたモデルを用い，累積下刈り作業時間を下刈りスケジュール別に推定した。選択されたモデルは，変数に期首雑草樹高，相対雑草樹高および植栽密度を含んでいた。選択されたモデルによるシミュレーションの結果，下刈り回数が 1 回減るたびに約 6%ずつ下刈り作業時間は短くなった。また，下刈りスケジュール別に見ると，連続して下刈りを実施したスケジュールで作業時間は短く，下刈り作業の期間が開いた場合に下刈り作業時間は長くなっていた。このことから，下刈りコスト削減のためには下刈りを連続で実施することが重要であることが示唆された。これらの結果から，下刈りコスト削減を検討するときは下刈り回数だけでなく下刈りスケジュールも検討する必要がある。

Chapter 5. The relationship between sugi height growth and weeding operation time: Assessment of optimal weeding schedules using Monte Carlo method.

（スギ樹高と下刈り作業時間の関係 - モンテカルロ法を使った最適下刈りスケジュールの検討 - ）

第 5 章では，6 年生時のスギ平均樹高と累積下刈り作業時間の関係を明らかにした。また，モンテカルロ法を用いて，スギの樹高成長が良く，下刈り作業時間の短い最適下刈りスケジュールの検討を行った。このとき，スギおよび雑草木の樹高期間成長量推定モデル，下刈り作業時間推定モデルを用いて植栽後 6 年目時点でのスギの樹高成長および累積下刈り作業時間を下刈りスケジュール別に推定した。また，下刈り回数が 3 回のスケジュール（全 20 通り）に着目し，スギの樹高および下刈り作業時間の観点からそれぞれの下刈りスケジュールを多重比較に基づき 3 つのグループに分け，最適な下刈りスケジュールを検討した。その結果，スギ樹高と累積下刈り作業時間の間には正の相関が見られ（ r ＝0.94），下刈り回数が 1 回減少するたび約 28（時間/ha）ずつ累積下刈り作業時間は減少した。スギの平均樹高は下刈り回数が異なっても同程度になる場合があった。また，最適下刈りスケジュールを検討した結果，植栽後 1，2 年目に下刈りを実施し，なおかつ下刈りと下刈りの期間が開いていないスケジュール（1，2，3 年目実施，1，2，4 年目実施，1，3，4 年目実施）が本対象地における最適下刈りスケジュールになり得ることが示された。

Chapter 6. The effects of competition between sugi and weed on both subsequent growth.
（スギと雑草木の競争関係がその後の両者の成長に与える影響）

第 6 章では, スギと雑草木の競争関係がその後のスギおよび雑草木の成長に与える影響を検討した。このとき，スギと雑草木の樹高成長の観点から下刈り終了基準の検討を行った。まず，従来の下刈り終了基準を適用した場合のスギおよび雑草木の樹高成長推移をスギ・雑草木樹高期間成長量モデルにより推定した。次に，相対雑草樹高およびスギ期首樹高の違いがその後の両者の成長に与える影響を検討した。その結果，従来の下刈り終了基準の 1 つであるスギ樹高 1.5m で下刈りを終了すると，スギが雑草木に追い越されていた。一方で，スギ樹高 2.0m で下刈りを終了すると，スギが雑草木に追い越されることは無かった。このことから， 下刈りを終了する際には 2.0m にスギが達している必要があると考えられた。また，スギ樹高が 2.0m の場合，相対雑草樹高が 0.3 以上になると下刈り終了後にスギが雑草木に追いつかれていた。これらの結果から，スギ期首樹高 2.0m かつ相対雑草樹高 0.3 以下が一つの下刈り終了基準になり得ることが示唆された。

Chapter 7. General Discussion

（総合考察）

本論ではスギの生存率，スギの樹高成長および下刈り作業時間から最適な下刈りスケジュールをした。あわせて，下刈り終了基準の検討を行った。本対象地における最適下刈りスケジュールは，植栽後 1，2 年目に実施し，下刈りと下刈りの期間を開けないスケジュール（植栽後 1，2，3 年目実施，1，2，4 年目実施および 1，3，4 年目実施）であると結論付けた。また，スギの樹高 2.0m かつ相対雑草樹高 0.3 以下が一つの下刈り終了基準となりうると結論付けた。

Acknowledgements

本論文を解析・執筆するにあたり，吉田茂二郎教授，溝上展也准教授，太田徹志博士，玉泉幸一郎准教授にご指導いただきました。入学当初は何もできなかった私がここまで成長できたのは先生方の丁寧なご指導のおかげです。鹿児島大学在学中とはまた違った雰囲気の中，勉学に励むことができました。厚く御礼申し上げます。また，鹿児島大学 寺岡行雄教授，加治佐剛准教授には現地調査ならびに論文執筆にご協力いただきました。九州大学に進学した際も多大なるご心配，ご迷惑をおかけいたしました。鹿児島に立ち寄った際にはいつも暖かく迎えてくださり，とても嬉しかったです。心より御礼申し上げます。調査地の管理をして下さった鹿児島大学付属高隈演習林の職員の皆さま，調査データの管理をしてくださった鹿児島大学 OB 金城智之氏，山下盛章氏，現地調査に協力してくれた鹿児島大学森林計画学研究室の皆さま，全国に類を見ない貴重な試験地のデータ蓄積があったからこそ，本論文を完成させることができました。今後もこの貴重なデータを引き継いでいく所存です。御礼申し上げます。

鳥取大学 岩永史子先生，統計数理研究所 伊高静博士には公私ともに相談に乗っていただきました。お二人のおかげで苦しいときも乗り越えることができました。御礼申し上げます。また，志水克人氏，伊藤一樹氏，小川みゆき氏をはじめとする研究室 OB のみなさんの力が無ければ私はここまで成長できなかったと思います。みなさんは私にとってはかけがえのない存在です。たくさん相談に乗ってくれてありがとう。ともに卒・修論の執筆に励んだ谷口寛昭氏，高橋麻耶氏とは様々なトラブルを一緒に乗り越えました。二人の存在は私の中で大きく，私も頑張ろうと思わせてくれました。ありがとう。植物代謝制御学研究室 渡辺敦史准教授，小林玄氏，造林学研究室 OB 國師周平氏には研究室が違うにも関わらず，たくさんのご助言をいただきました。ひと時の休息を一緒に過ごせてとても楽しかったです。御礼申し上げます。

たくさんの人に支えられ，大事もなく三年間を過ごすことができました。皆さまのお力添えが無ければここまで来ることはできなかったと思います。厚く御礼申し上げます。最後に，私のわがままを許してくれた家族，そして研究に対して理解を示してくれた友人に感謝申し上げます。

平成 29 年某日

福本　桂子

Reference

Akai T, Yoshimura K, Honjyo T (1987) Structure and growth of sugi (*Cryptomeria japonica*) thirifity stand with extensive tending. Bull Kyoto Univ For 59:31–42

Balandier P, Collet C, Miller JH, Reynolds PE, Zedaker SM (2005) Designing forest vegetation management strategies based on the mechanisms and dynamics of crop tree competition by neighbouring vegetation. Forestry 79:3–27. doi: 10.1093/forestry/cpi056

Biring B, Comeau P, Fielder P (2003) Long-term effects of vegetation control treatments for release of Engelmann spruce from a mixed-shrub community in Southern British Columbia. Ann For Sci 60:681–690

Dacosta J, Szuba K, Bell F, Moore T, Lennon K, Leach J, Bazeley D, Luckai NJ (2011) Modelling landscape-level effects of reduced herbicide use in two forests in northern Ontario. For Chron 87:290–309

Dampier JJEE, Bell FW, St-Amour M, Pitt DG, Luckai NJ (2006) Cutting versus herbicides: Tenth-year volume and release cost-effectiveness of sub-boreal conifer plantations. For Chron 82:521–528. doi: 10.5558/tfc82521-4

Forestry Agency (2016) Annual report on forest and forestry in Japan. Zenrinkyo, Tokyo

Franceschi J De, Bell FW (1990) Labor Productivity and costs of mortor-manual release of spluce from hardwoods in Manitoba. For Can, Northwest Reg, North For Cent, Edmonton, Alberta Inf Rep NOR-X-312 1–13

Fukuchi S, Yoshida S, Mizoue N, Murakami T, Kajisa T, Ota T, Nagashima K (2011) Analysis of the Planting Density toward Low-cost Forestry: a Result from the Experimental Plots of Obi-sugi Planting Density. J Japanese For Soc 93:303–308. doi: 10.4005/jjfs.93.303

Fukumoto K, Ota T, Mizoue N, Yoshida S, Teraoka Y, Kajisa T (2017) The effect of weeding frequency and timing on the height growth of young sugi (*Cryptomeria japonica*) in southwestern Japan. J For Res 204–207. doi: 10.1080/13416979.2017.1322347

Fukumoto K, Teraoka Y, Kajisa T, Hagino K, Yamashita M, Kinjou T (2015a) Comparison of the growth of planted sugi (*Cryptomeria japonica*) and the state of competition among different weed control periods. Kyushu J Res 3–6

Fukumoto K, Teraoka Y, Kinjou T, Yamashita M, Kajisa T, Ugawa S, Ashihara S, Oka M (2015b) Competition between young Japanese cedar (*Cryptomeria japonica*) and broad-leaved trees at different slope positions in a non-weeded stand in Southern Kyushu. Japanese J For Plan 49:43–49

Hiraoka Y, Shigenaga H, Yamagawa H, Okamura M, Chigira O, Fujisawa Y (2013) Effect of non-weeding and subsequent improvement cutting on the growth of *Cryptomeria japonica* clones. J Japan For Soc 95:305–311

Hirata R, Ito S, Eto K, Sakuta K, Mizoue N, Mitsuda Y (2015) Early growth of hinoki (Chamaecyparis obtusa) trees under different topography and edge aspects at a strip-clearcut site in Kyushu, Southern Japan. J For Res 20:522–529. doi: 10.1007/s10310-015-0508-z

Hirata R, Ito S, Yamagawa H, Shigenaga H, Takagi M (2012) Influence of non-weeding treatment on the early growth of planted hinoki (Chamaecyparis obtusa) trees. J Japanese For Soc 94:135–141

Homagain K, Shahi C, Leitch M, Luckai N, Wayne Bell F (2011a) Differences in extrinsic tree quality and value of fibre production following alternative vegetation management treatments in northwestern Ontario. For Chron 87:251–259. doi: 10.5558/tfc2011-012

Homagain K, Shahi C, Luckai N, Leitch M (2011b) Benefit–cost analysis of vegetation management alternatives: An Ontario case study. For Chron 87:260–273

Ito A, Watano Y, Hakamata T, Yamamoto S, Kondo A (2015) The Effects of Weeding Method and Planting Density of Japanese Cedar (*Cryptomeria Japonica*) and Japanese Cypress (*Chamaecyparis Obtusa*) on the Operational Efficiency of Weeding and Early Growth of Trees. Bull Shizuoka Res Ins Agr 8:89–93

Itou T, Yamada Y (2001) Analysis of Workload and Weed Suppression Effects from Changing the Brush-cutting Season. J Japanese For Soc 83:191–196. doi:

10.11519/jjfs1953.83.3_191

Kawana A, Kataoka H (1981) Silviculture, 3rd edn. Asakura shoten, Tokyo

Kinjou T, Teraoka Y, Ashihara S, Inokura Y, Ura M (2012) Inventory data of different weeding frequencies plots in the Takakuma experimental forest compartment 16, Kagoshima University (2006~2011). Res Bull Kagoshim Univ 39:45–48

Kinjou T, Teraoka Y, Ashihara S, Takeuchi I, Inokura Y (2011a) The growth and states of planting trees under different weeding control operation patterns in Kagoshima Pref., Japan. Kyushu J Res 64:56–59

Kinjou T, Teraoka Y, Ashihara S, Takeuchi I, Inokura Y, Ura M (2011b) The operational efficiency in weeding under weeding frequencies. Res Bull Kagoshima Univ 38:7–11

Kitahara F, Watanabe N, Mitsuda Y, Yamagawa H, Sakai A, Tarumi A (2013) The relationship among growth, working hours, and workload by difference of weeding schedule on replanted Sugi (*Cryptomeria japonica*) forests. Soc Appl For Sci 124:415. doi: 10.11519/jfsc.124.0.415.0

Kobe R, Pacala S, Silander J (1995) Juvenile tree survivorship as a component of shade tolerance. Ecol Appl 5:512–532

Korb J, Fulé P, Stoddard M (2012) Forest restoration in a surface fire-dependent ecosystem: An example from a mixed conifer forest, southwestern Colorado, USA. For Ecol Manage 269:10–18. doi: 10.1016/j.foreco.2012.01.002

Little K, Willoughby I, Wagner R, Adams P, Frochot H, Gava J, Gous S, Lautenschlager R, Orlander G, Sankaran K, Wei R (2006) Towards reduced herbicide use in forest vegetation management. South African For J 207:63–79

Maeda U (1999) The factors inhibiting the maturation of the broad-leaved artificial forest : Miscutting damage by brush cutting occurring on a large plantation. App Sci 125–128

Mallik A, Bell FW, Gong Y (2002) Effectiveness of delayed brush cutting and herbicide treatments for vegetation control in a seven-year-old jack pine plantation in northwestern Ontario, Canada. Silva Fenn 36:505–519

Mason E (2006) Interactions between influences of genotype and grass competition on growth and wood stiffness of juvenile radiata pine in a summer-dry environment. Can J For Res 36:2454–2463

Miller J, Zutter B, Newbold R, Edwards M, Zedaker S (2003) Stand dynamics and plant associates of loblolly pine plantations to midrotation after early intensive vegetation management—a southeastern United States regional. South J Appl 27:1–16

Nakagawa S, Schielzeth H (2013) A general and simple method for obtaining R2 from generalized linear mixed‐effects models. Methods Ecol Evol 4:133‐142

Ogata N, Nagatomo Y (1971) A few suggestion to the object of weeds control on the Japanese Plume-grass (Miscanthus sinensin Andress) community and its ecological aspect in silviculture. J Weed Sci Tech 12:

Ota T, Takahira S, Nakama K, Yoshida S, Mizoue N (2013) Effectiveness of Low-density Planting in Terms of Planting Cost Reduction and Felling Income Reduction. J Japanese For Soc 95:126–133. doi: 10.4005/jjfs.95.126

Pitt D, Dumas M, Wall R, Thompson D, Lanteigne L, Hintz W, Sampson G, Wagner R (1999) Chondrostereum purpureum as a biological control agent in forest vegetation management. I. Efficacy on speckled alder, red maple, and aspen in eastern Canada. Can J For Res 29:841–851. doi: 10.1139/x99-122

Plummer M (2003) JAGS: A program for analysis of Bayesian graphical models using Gibbs sampling. DCS 2003 Work Pap

R Core Team. 2014. R: a language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. URL: http://www.R-project.org/

Roy V, Dubeau D, Auger I (2010) Biological control of intolerant hardwood competition: Silvicultural efficacy of Chondrostereum purpureum and worker productivity in conifer plantations. For Ecol Manage 259:1571–1579

Sakaguchi (1983) Sugi. Tokyo: Zenrinkyo

Sakura T, Kawana K, Karakama I, Enoki S (1987) Structure of weed communities in two young plantation of Sugi (*Cryptomeria japonica*) and Hinoki (Chamaecyparis obtusa). Trans of J For Soc 98: 317-318.

Sasaki Y, Takeuchi I, Teraoka Y (2009) Relathionship between planting tree densities and its growth-case of 34-years-old Hinoki (*Chamaecyparis obtusa*) stand-. Kyushu J Res 62:14–17

Scarbrough SL, Jackson C, Marchman S, Allen G, Louch J, Miwa M (2015) Herbicide Concentrations in First-Order Streams Establishing Pine Plantations. For Sci 61:604–612

Shigenaga H, Nomiya H, Araki, G M, Yamagawa H (2012) The initial growth of sugi surpressed by pampas grass. Ann Rep Kyushu Res Cen 2012

Shimozono T, Uwatoko S, Oosako M (2009) The effect of weeding practice on sugi (*Cryptomeria japonica*) growth. Kyushu J Res 62:80–83

Stokes V, Willoughby I (2014) Early weed control can increase long-term growth, yield and carbon sequestration of Sitka spruce stands in Britain. Forestry 87:425–435

Strahan R, Stoddard M, Springer J, Huffman D (2015) Increasing weight of evidence that thinning and burning treatments help restore understory plant communities in ponderosa pine forests. For Ecol Manage 353:208–220. doi: 10.1016/j.foreco.2015.05.040

Tange T, Suzuki M, Yagi H, Sasaki S, Minamikata Y (1993) Influence of the weeding method on the growth of planted trees. J Japanese For Soc 75:416–423

Tanimoto T (1982) Analysis of growth of Sugi (*Cryptomeria japonica*) and natural vegetation in the young sugi plantation. Bull Prod Res Inst 55–122

Thiffault N, Hébert F, Charette L, Jobidon R (2014) Large spruce seedling responses to the interacting effects of vegetation zone, competing vegetation dominance and year of mechanical release. Forestry 87:153–164

Thiffault N, Roy V (2011) Living without herbicides in Québec (Canada): Historical context, current strategy, research and challenges in forest vegetation management. Eur J For Res 130:117–133. doi: 10.1007/s10342-010-0373-4

Tsurusaki S, Sasaki S, Shigenaga H, Yamagawa H (2016) The effect of weeding on growth of young sugi (*Cryptomeria japonica*) and recovered weed trees. Kyushu J For Res 69:99–102

Tsutsumi T (1994) Silviculture. Tokyo: Buneidōshuppan

Uemura K, Taniguchi S (2004) Retardation of weed growth by sheets made from strips of Sugi veneer. Soc Appl For Sci 13:151–154

Ukon K, Takeuchi I (2011) The actual weeding in southern Kyushu- Regeneration of weed and miscutting-. Kyushu J Res 39–41

Wagner R, Little KMK, Richardson B, McNabb K (2006) The role of vegetation management for enhancing productivity of the world's forests. Forestry 79:57–79. doi: 10.1093/forestry/cpi057

Wagner R, Mohammed G, Noland T (1999) Critical period of interspecific competition for northern conifers associated with herbaceous vegetation. Can J For Res 29:890–897

Wagner R, Noland TL, Mohammed GH (1996) Timing and duration of herbaceous vegetation control around four northern coniferous species. New Zeal J For Sci 26:39–52

Watanabe N, Tokuhisa K, Fukada H, Fujimoto K (2013) sugi growth and quality under weeding frequency reducing

Wiensczyk A, Swift K, Morneault A, Thiffault N, Szuba K, Bell F (2011) An overview of the efficacy of vegetation management alternatives for conifer regeneration in boreal forests. For Chron 87:175–200

Yamagawa H, Shigenaga H, Araki, G M, Nomiya H (2016) Effects of Initial Size and Surround- ing Weed Trees on Height Growth of Planted Sugi (*Cryptomeria japonica*）

Trees in Kyushu, Japan. J Japanese For Soc 98:241‑246

Yee TW (2010) The VGAM Package for Categorical Data Analysis. JSS J Stat Softw 32:

Yokoi S (2001) The effect of ommition of weeding on the forest structure in the plantation of Zelkiva serrata. Bull Gifu Pref Sci Res 1–8

Yokoi S, Mizutani Y, Yokotani Y, Yamaguchi K (1999) Damages of eight species hardwoods during seven years after plantation in the snowy region. Bull Gifu Pref Sci Res 1–8

Yukutake K, Yoshimoto A (2001) Cost analysis of timber production from domestic resources. Japan J For Plan 35:75–80

Appendix (Summary of field measurement data)

Table A.1. The summary of the number of sugi mortality trees under different slope aspect and weeding schedules. Hyphen indicates that field measurements were not conducted.

Slope aspect	Weeding schedules	Initial planting density (tree/ha)	Number of initial sugi trees	Number of mortality trees						Total
				2007	2008	2009	2010	2011	2012	
North	Every year	1,500	63	-	-	2	0	0	0	2
	2,4,5,6	1,500	62	-	-	5	0	0	1	6
	3,4,5,6	1,500	58	-	-	7	1	1	3	12
	1,3,5	3,000	61	-	-	4	1	1	0	6
	2,3,4	3,000	57	-	-	2	0	0	0	2
	1,2,3	1,500	60	-	-	2	0	0	0	2
	Non weeding	3,000	60	-	-	19	1	1	1	22
South	Every year	1,500	65	-	-	10	0	0	0	11
	2,4,5,6	1,500	61	-	-	4	0	0	0	4
	3,4,5,6	1,500	62	-	-	5	0	0	0	5
	1,3,5	3,000	61	-	-	2	1	0	0	3
	2,3,4	3,000	62	-	-	4	1	0	0	5
	1,2,3	1,500	62	-	-	0	0	0	0	0
	Non weeding	3,000	60	-	-	3	0	0	0	3

Table A.2. The summary of the number of accidental cutting sugi trees under different slope aspect and weeding schedules. Hyphen indicates that field measurements were not conducted.

Slope aspect	Weeding schedules	Initial planting density (tree/ha)	Number of initial sugi trees	Number of accidental cutting trees						Total
				2007	2008	2009	2010	2011	2012	
North	Every year	1,500	63	0	0	0	0	0	0	0
	2,4,5,6	1,500	62	0	0	0	1	0	0	1
	3,4,5,6	1,500	58	0	0	4	2	1	0	7
	1,3,5	3,000	61	1	0	0	0	0	0	1
	2,3,4	3,000	57	0	0	0	0	0	0	0
	1,2,3	1,500	60	0	0	0	0	0	0	0
	Non weeding	3,000	60	0	0	0	0	0	0	0
South	Every year	1,500	65	0	0	0	0	0	0	0
	2,4,5,6	1,500	61	0	1	0	3	3	0	7
	3,4,5,6	1,500	62	0	0	1	3	1	0	5
	1,3,5	3,000	61	-	-	2	0	2	0	4
	2,3,4	3,000	62	-	-	3	3	0	0	6
	1,2,3	1,500	62	0	0	0	0	0	0	0
	Non weeding	3,000	60	0	0	0	0	0	0	0

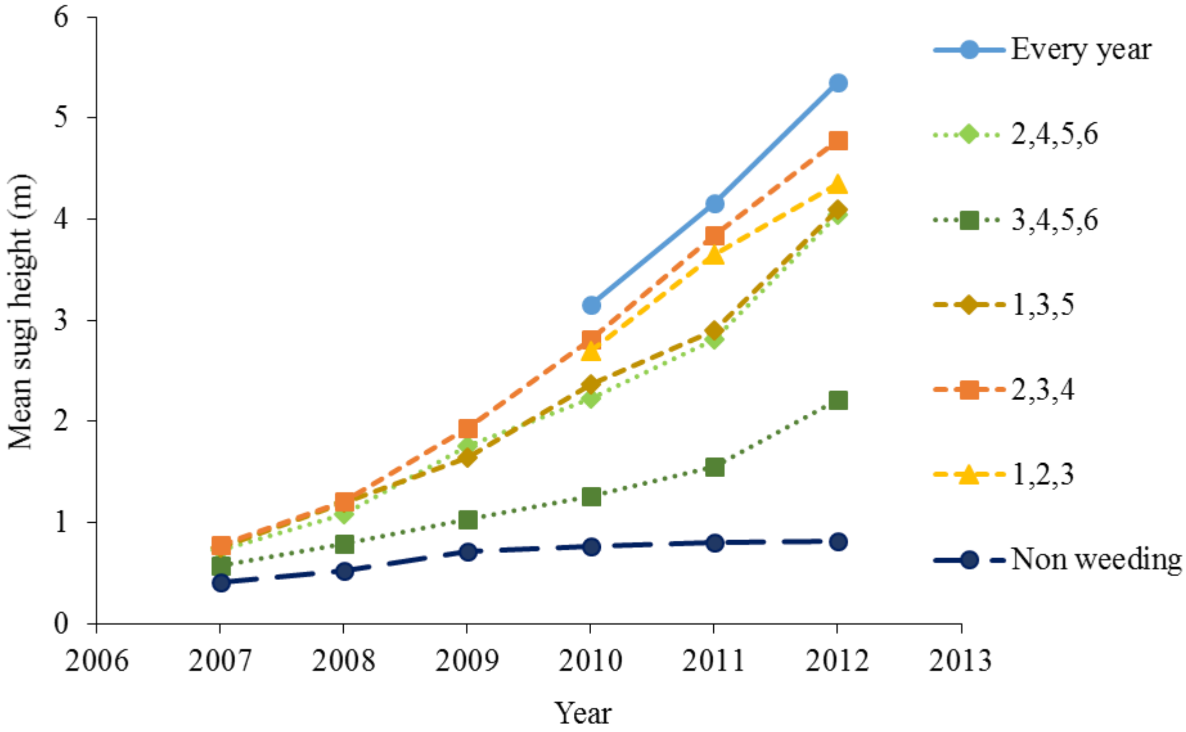

Figure A.1. The sugi mean height on North facing slope under different weeding schedules.

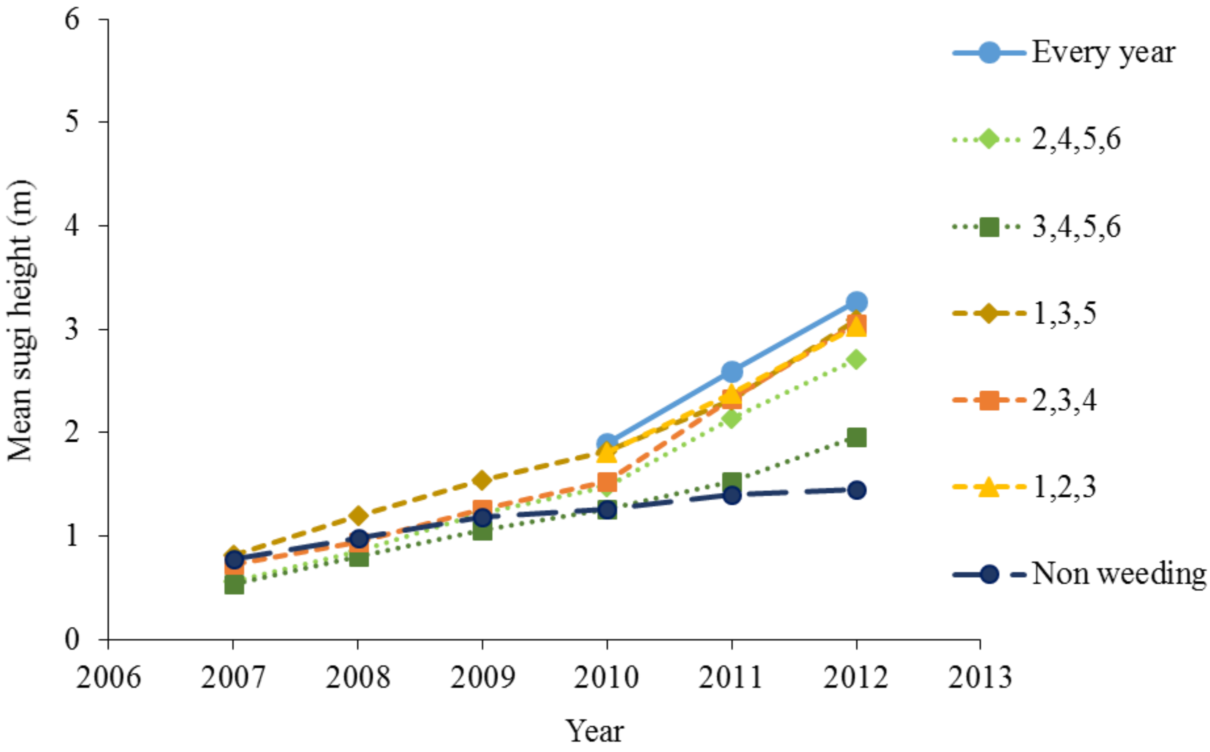

Figure A.2. The sugi mean height on South facing slope under different weeding schedules.

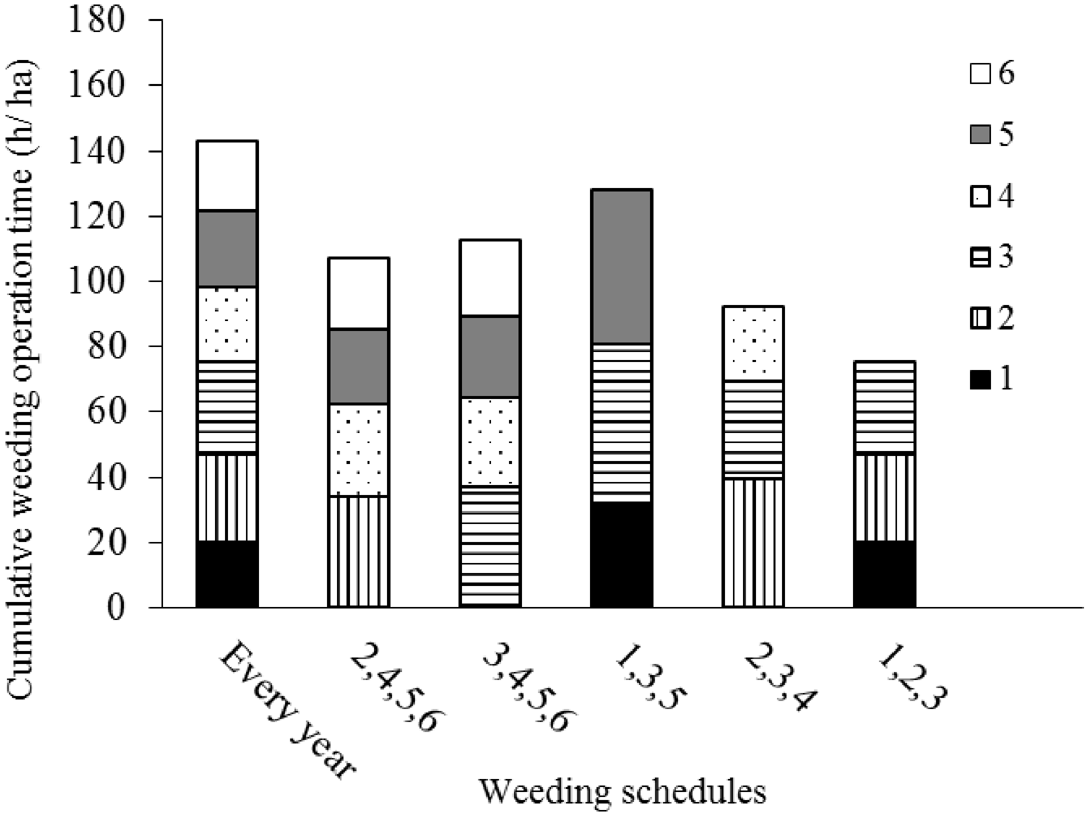

Figure A.3. Cumulative weeding operation time on North facing slope under different weeding schedules. The legend indicates weeding conducted year.

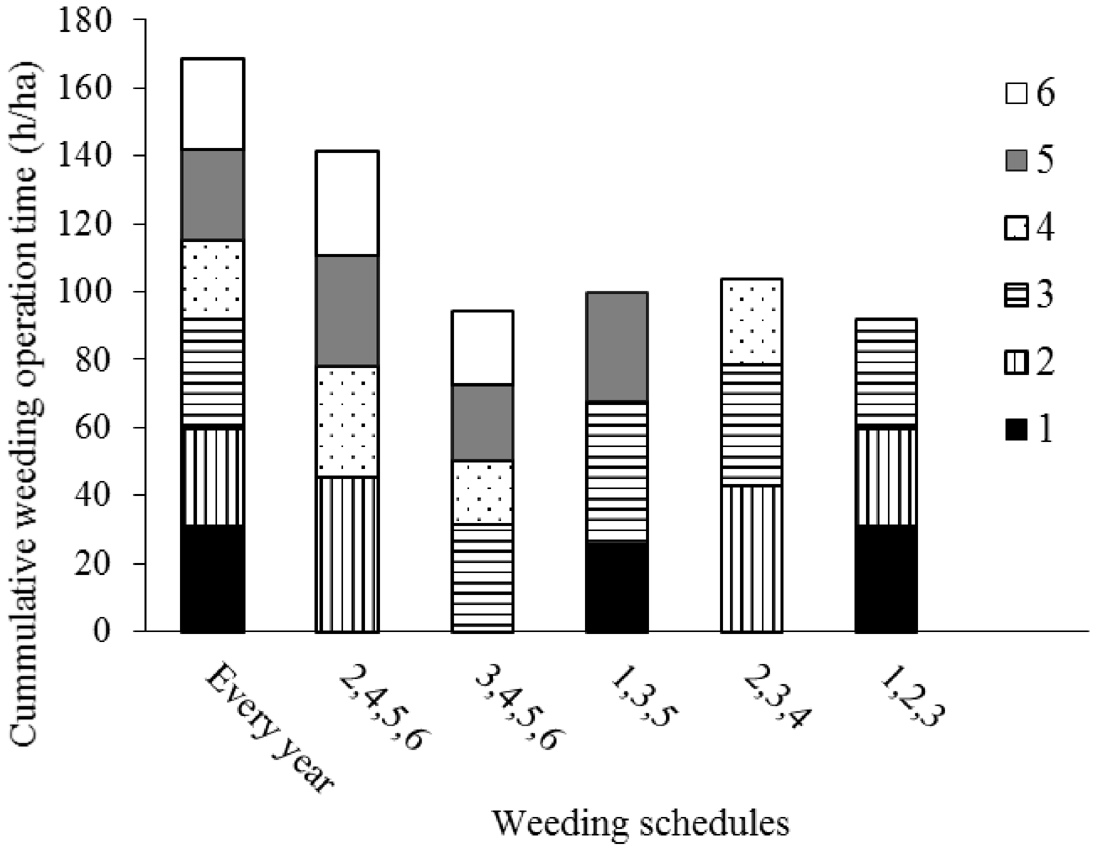

Figure A.4. Cumulative weeding operation time on South facing slope under different weeding schedules. The legend indicates weeding conducted year.