Thinning Effects on Forest Stands and Possible Improvement in a Stand Reconstruction Technique

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ABSTRACT

I tested the effects of artificial thinning on estimated forest stand variables (aboveground biomass, total stem volume, stem volume growth, and stand density) for even-aged plantations by a stand reconstruction technique that does not require data collection in the plot in previous years. Furthermore, I examined possible improvement of the estimated stand variables (resulted from the thinning effects) with the stand reconstruction technique by including stump information (tree rings; stump diameter) in the analysis.

In examining the thinning effects in Japanese cedar (Sugi) and cypress (Hinoki) plantations, twenty-six sample trees were collected from the Experimental Forest plots in Gifu Prefecture of central Japan. Sugi stands received two thinning operations in 1980 and 1998, while Hinoki stand experienced thinnings three times in 1973, 1977 and 2003. Stem analysis data were gathered in 2006 and 2007 for Sugi and Hinoki, respectively. Results showed that percentage error of the estimated variables varied within ±65% (Sugi) and ±73% (Hinoki) of the observed values for years before the thinning events. The 95% confidence intervals of the estimated means by the bootstrap method further accentuated for large extent of the prediction error which were generally underestimated for years before the thinning operations in both Sugi and Hinoki stands.

In order to examine the thinning effects in spruce and fir plantations, thirty sample trees of *Abies sachalinensis*, *Picea jezoensis* and *Picea glehnii* were collected in six plantations at Hitsujigaoka Experimental Forest in Hokkaido, Japan. Stem data gathered in 2013 from six stands were used to estimate the forest stand variables in the past by the stand reconstruction technique, and their accuracy was tested with the values calculated from the census data of the previous years. Results showed that percentage error of the estimated variables varied within ±20% of the observed values for the years after the thinning events. However, the estimates were underestimated (as large as 40%) for the years before the thinning operations. The 95% confidence intervals of the estimated means by the bootstrap method further emphasized the effects of thinning before the thinning operations, especially in *Abie sachalinensis*.

Overall, results from Japanese cedar, Japanese cypress, Spruce and Fir plantations suggested that thinning caused substantial underestimation of stand variables for the years before the thinning operations, suggesting that caution must be exercised in interpretation of predictions by the stand reconstruction technique.

Finally, I tested the possible improvement in the underestimated stand variables in Spruce and Fir plantations by including stump information. Results showed that accuracy of the estimated variables can be improved by alleviating underestimation after adding old stumps. Without adding data from the stumps, percentage error of estimates of the stand variables varied within ±20% of the observed values. By including the stumps, the percentage error of the estimates of the same stand variables generally fell within ±15% for the years after 1997. The 95% confidence intervals of the estimated means by the bootstrap method further reported that adding stumps does not always improve the prediction in stand density; but generally, improve the predictions in aboveground biomass, stem volume and stem volume growth. Overall, sudden changes in aboveground biomass and stand density through thinning operations were reproduced better, although the degree of improvement is sometimes minimal, by incorporating information of the stumps to the analysis by the stand reconstruction technique for all 3 species examined. Thus, taking into account of information from already dead individual trees is likely to improve predictions of stand variables, and should generally be considered as a part of the standard method of the stand reconstruction.

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CHAPTER 1
General Introduction

The main focus of the discipline of ecology was to understand the relationships between organisms and their environments. Ecological research is often carried out over relatively short periods of time. But ecological knowledge based on short time scales may not be applicable to long-term ecological dynamics. In other words, the complexity of modern ecological processes may not be detectable on the bases of short-term investigations; it needs decades or longer periods to investigate their dynamics and evaluate their consequences. The need for long-term ecological studies was formulated more than 30 years ago (Likens 1983, 1989; Franklin 1989; Risser 1991).

The long-term ecological research aims to understand the interrelationships between environmental changes and ecosystem developments. The ecological events for which long-term studies are considered as essential include: slow process (e.g. forest succession); rare events (e.g. ecological disturbances such as drought or insect outbreaks); processes with high variability including litterfall in mature deciduous hardwood forests (Gosz et al. 1972) and in old-growth Douglas-fir forests in the Pacific Northwest (Art McKee, personal communication).

What supplements long-term ecological research is retrospective studies, which uses paleoecological, dendrochronological, historical and other approaches in order to measure ecosystem responses to rare events (Strayer et al. 1986) and predicts the future consequences. Retrospective studies have recently become of interests to foresters and ecologists since these studies can generate valuable ecological insights. The science of tree-ring dating, which is also known as dendrochronology, is an example of such retrospective studies.

It is well known that, by just counting the growth rings in the lower part of the stem, approximate age of a temperate tree can be determined. Tree-ring records are considered as natural archives from which information such as forest fire, insect outbreaks, and other ecological signals can be retrieved. These data from tree rings can be dated back to decades or even centuries to investigate the history of tree growth and stand development in a specific location. Precise dating from ring widths is plausible since tree growth is frequently affected by variations in climate, and all the events (wet and dry or warm and cold) are recorded by the sequences of wide and narrow rings in a large number of trees. The patterns of wide and narrow rings are visible not only in living trees, but also in stumps and the wood of trees from nearby areas. Tree-ring patterns from the same trees, and between trees from different locations are matched to ascertain that each tree ring corresponds to the exact year of its formation. This procedure is called crossdating, which is the most basic principle in dendrochronology. The procedure is essential in detecting missing or absent rings.

Recently, numerous tree-ring based studies have been conducted to elucidate the relationships between climate variables and tree-ring patterns and also to reconstruct the past forest stand development. Reconstructive studies or historical stand reconstruction have been endorsed by scientists and researchers as a technique which can be used to learn about successional development, disturbance history, changes in species composition and spatial patterning and changes in climate (Morrow 1985; Duncan and Stewart 1991; Taylor and Halpern 1991). Some of these studies conducted in the past were based mostly on dead plant materials such as stumps, snags and dead plant materials (Oliver and Stephens 1977; Harrod et al. 1999; Peter and Harrington 2010), while others were based on both dead plant materials and tree-ring records of living individuals (Henry and Swan 1974).

Another method, which has similar objective to other stand reconstruction techniques, was proposed by Osawa et al. (2000) for quantitatively reconstructing structural development of even-aged monospecific forests. The difference from the previous method is that the newly proposed method deals only with the living plant materials. The method considers that the past stand structure is recorded in the tree-ring patterns and could be traced to the distant past. The method is based on two basic assumptions: (1) general form of the frequency distribution function in aboveground mass (or stem volume) of individual trees in a stand is conserved over time of the stand development; and (2) parameters of this frequency distribution function of tree size can be estimated for a given time in the past from tree-ring and other data presently available. Knowledge on the tree size distribution in the past enables us to calculate values of stand biomass for a specified time. Therefore, quantitative reconstruction of stand development is plausible (Osawa et al. 2005). In fact, Osawa and Abaimov (2001) and Osawa et al. (2001) showed that stem size distribution in a forest stand can be consistently described by the beta-type distribution function (Hozumi 1971), and its change over time by the changes in its parameter values. The method was first used by Osawa et al. (2000) to show that the frequency distribution of stem volume for a *Larix gmelinii* stand in Siberia can be described for about 80 years in the past. Then, the method was further developed and tested by Osawa and Abaimov (2001) and Osawa et al. (2005) to examine its applicability in estimating the current values of the frequency distribution of individual stem volume, total stem volume of a stand and aboveground biomass. These tests were conducted primarily for examining accuracy in reconstructing pattern of tree size distribution. The last investigation of the method to reconstruct structure of single-species stands in the past was done in 2005. The method was introduced to reconstruct stand variables such as aboveground biomass, stem volume, stem volume growth and stand density of even-aged *Abies sachalinensis* stands (Osawa et al. 2005). The history of these forest stands in this study indicated that disturbance events (e.g. artificial thinning) did not occur during the period of investigation. However, it is natural that forest stands encounter disturbances in the process of growing and occupying a particular area. Therefore, investigating the effects of disturbance on the estimated stand variables by the stand reconstruction technique is essential in understanding the applicability of the technique working under different natural conditions, especially when varying degrees of thinning are applied to a specific plantation. Previous study revealed that thinning induced underestimation of the estimated stand variables (aboveground biomass, stem volume and stand density) by the stand reconstruction technique (Fujii 2014). Therefore, it is important to clarify if underestimation is the general characteristic of the method when the stands are influenced by disturbances in the past. Corrections for estimated stand variables under the influence of disturbances such as thinning operations is another subject that is to be dealt with in the present study. In general, thinning creates snags, logs and other woody debris (Hartly 2002). For this reason, it is possible that information from the dead plant materials could be used to improve the estimates of the stand reconstruction technique.

I explore in the present study possible corrections of estimated stand variables by the stand reconstruction technique, proposed by Osawa et al. (2000, 2005), by including stump information remaining in monospecific species stands that experienced different degrees of artificial thinnings. In other words, stump information such as diameter at stump height, and tree-ring records on stumps will be used in our study. More specifically, if the individual tree size is distributed as the beta-type distribution function in a stand, $M(w)$ defined as the mean of the tree size for individuals larger than the size w will be related linearly with w. This linear relationship defines values of the parameters of the beta-type distribution. Therefore, if we have an additional information (or the estimate) of the size of the smallest living tree in the stand, we have complete information for describing the size structure of the trees in the stand. Now, assuming that larger trees in the stand are likely to have been the members of the population from the beginning of stand establishment, and that the size of the individual trees in the past can be estimated from tree rings, it will become possible to reconstruct the $M(w)$-w relationship for a given year in the past. Therefore, the size structure of the trees in the stand in the past can be estimated quantitatively. Then, using this knowledge of size structure distribution, we could calculate various stand variables for a given year in the past. Chapter 1 is a general introduction. Chapter 2 explains the effect of thinning disturbance on estimated stand statistics by the stand reconstruction technique with a case of Sugi and Hinoki plantations. Chapter 3 also demonstrates the effect of thinning disturbance on estimated stand statistics by the stand reconstruction technique, but with a case of Spruce and Fir plantations. It is noted that the degrees of thinning in the case of Sugi and Hinoki stands are heavier than the case of Spruce and Fir stands. Chapter 4 introduces possible corrections for the disturbance effect by incorporating information of stumps into the analysis. This chapter describes possible corrections of estimated stand variables in the case of Spruce and Fir stands, but not of Sugi and Hinoki stands. Chapter 5 provides a general discussion and conclusion about the disturbance effects on the stand reconstruction technique and whether the improvement can be seen or not after including stump information.

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CHAPTER 2

Effects of Thinning Disturbance on Stand Variables Estimated by the Stand Reconstruction Technique in Japanese Cedar and Cypress Plantations

Summary

This chapter examined the effects of artificial thinning on the estimated stand variables (aboveground biomass, total stem volume, stem volume growth, and stand density) by a stand reconstruction technique that does not rely on data collected in the plot in previous years. Twenty-six sample trees of Japanese cedar (*Cryptomeria japonica*) and Japanese cypress (*Chamaecyparis obtusa*) were collected from the Experimental Forest plots in Gifu Prefecture of central Japan. Japanese cedar (Sugi) stands received two thinning operations in 1980 and 1998, while Japanese cypress (Hinoki) stand experienced thinnings three times in 1973, 1977 and 2003. Stem analysis data and census data were both gathered in 2006 and 2007 for Japanese cedar and Japanese cypress, respectively. Then, the stand variables were estimated using the stand reconstruction technique, and the prediction accuracy were compared to observed values calculated from census data for the years 1979, 1982, 1984, 1985, 1989, 1998, and 2006 for Japanese cedar and 1973, 1977, 1983, 1992, 1997, 2003, and 2007 for Japanese cypress. Results showed that percentage error of the estimated variables varied within ±65% (Japanese cedar) and ±73% (Japanese cypress) of the observed values for years before thinning events. The 95% confidence intervals of the estimated means by the bootstrap method further accentuated for large extent of the prediction error for years before the thinning operations in both Japanese cedar and Japanese cypress stands. Overall, the analysis suggested that thinning caused substantial underestimation of stand variables with the current stand reconstruction technique for the years before thinning operations, suggesting that caution must be exercised in interpretation of predictions.

2.1 Introduction

Forest reconstruction studies have been conducted to assess long-term trends in forest stand dynamics, which provide ecological insights and essential knowledge for informed decision making in the context of sustainable forest management. This kind of study uses tree rings for analysis following the techniques developed in dendrochronological research. Tree rings can be used to establish past history of forests. When precise dates can be obtained from tree rings, past events such as climatic changes, volcanic eruption and fire could be inferred.

Tree ring-based studies, which aim to understand changes in forest history and to predict future growth of the forests, have been applied in temperate old-growth forests in the United States (e.g. Foster et al. 1996), boreal forest in Siberia (e.g. Osawa et al. 2000) and Canada (Metsaranta et al. 2008; 2018), cool-temperate conifer forests in Japan (e.g. Osawa et al. 2005), and European forests (e.g. Spiecker et al. 1996; Spiecker 2002). Source of information from tree rings can also be used to analyse past growth of trees and establish patterns for predicting future growth (Avery and Buckhart 2002). Retrieving complete stem analysis data is the most accurate method to derive accumulated stem volume growth of individual trees (Husch et al. 2003). In addition, relationships between tree sizes (diameter, height or volume) and age of trees can infer stand structures and enable assessment of the population dynamics of forests through building size class frequency distribution (Stewart 1986; Bergeron 2000; Xing et al. 2012).

The notion that past events such as disturbances (e.g. thinning, fire and insect outbreak) or climatic change can be understood from tree ring analysis has captured interests of scientists around the world. Similarly, in Japan, reconstruction of past forest structure and climatic events have been carried out using dendrochronological approaches to understand such events. For understanding climatic events, Yonenobu and Eckstein (2006) used tree-ring width of Hinoki cypress to reconstruct early spring temperature for central Japan. Osawa et al. (2005)

applied another approach called a stand reconstruction technique to reconstruct past biomass, tree volume and stand density. However, effects of disturbances (e.g. artificial thinning) have never been examined fully on the stand reconstruction technique (Osawa et al. 2000, 2005), which was proposed as an approach complementary to other methods in reconstructing long-term changes in forest structure.

The purpose of this study was to investigate the effects of artificial disturbance (e.g. thinning) on the estimated stand variables in the past by the proposed method of stand reconstruction (Osawa et al. 2000, 2005) in the thinned conifer plantations of Japanese cypress (Hinoki) and Japanese cedar (Sugi). In other words, the effects of thinning disturbance on the accuracy of the estimates by the stand reconstruction technique could be explained through comparison of reconstructed values of aboveground biomass, total stem volume, stem volume growth and stand density to those observed during previous stand measurements. The present study did not take into account the effects of thinning methods and how such methods could affect the result of predictions. Instead, the study mainly focused on how accurate the stand reconstruction technique was in predicting forest stand variables, given that thinning events occurred in a particular plantation.

2.2 Materials and methods

2.2.1 Site description and stand measurement

This study was conducted at Yamato district in Gujo for Japanese cedar (*Cryptomeria japonica*) and at Ena for Japanese cypress (*Chamaecyparis obtusa*) plantations both in Gifu Prefecture of central Japan in which an experiment on artificial thinning was performed. Soil type is Andosols (FAO 2014) or Andisols (USDA 2010) for both species and is one of the common soils found in volcanic regions of Japan.

The Japanese cedar (Sugi) stands (35°51'N 136°57'E) were located on a lower part of the west-facing slope with a slope-inclination of 15^{o} on average at an altitude of approximately

800 m a.s.l. The study was conducted using Sugi plantations established in 1958 for an experiment on artificial thinning. Initial thinning operations were carried out in 1980 by removing certain proportions of the number of stems at varying intensity (Treatment A: 24%; Treatment B: 34%; Treatment C: 45%; and Treatment D: No thinning). Additional thinning was conducted in 1998. In this thinning, stems were removed so that stand density became similar in Treatment A, B and C. The thinning ratios were 44%, 39% and 20% by the number of removed trees, and 33%, 13% and 18% by basal area, for plots A, B and C, respectively. Plot D was a control. In both events (1980 and 1998), thinning operations were done by mainly removing small trees. As a result, there were no trees with a diameter at breast height smaller than 15 cm in Treatments A, B and C in 2006 (Appendix 2-1). It is noted that the estimates of the stand variables by the stand reconstruction technique are affected mostly by the thinning of 1998. Measurement area was established within each plot by excluding stems that are likely to be affected by the trees at the periphery of the plot or by those outside of the plot. The plot area was 800, 700, 700 and 600 m^2 for plots A, B, C and D, respectively (Obora et al. 2008).

The Japanese cypress (Hinoki) stand (35°25'N 137°28'E) was established in 1953 and located at an altitude of approximately 540 m a.s.l. The planting density at the time of establishment was 3000 stems per hectare. Thinning operations were conducted by removing certain proportions of the number of stems at the ratios of 18%, 40% and 34% for 1973, 1977, and 2003, respectively. The plot area was 450 m^2.

2.2.2 Stand measurement and stem disk collection

For the Sugi stands, DBH was measured in 1979, 1982, 1984, 1985, 1989, 1998, and 2006; whereas, tree height measurement was done only for selected years in 1979, 1984, 1998 and 2006. Seventeen sample trees of various sizes (Treatment A= 5 trees, Treatment B = 4 trees, Treatment C = 4 trees, Treatment D = 4 trees) were selected and cut in 2006 for collecting stem disks at various distances from the stem base: 0 m, 1.3 m, 3.3 m, and upwards at 2 m intervals throughout the length of the stem.

For the Hinoki stand, measurement of DBH was conducted in 1973, 1977, 1983, 1992, 1997, 2003 and 2007; however, tree height was measured only in 2003 and 2007. Nine sample trees of various sizes were felled in 2007 for collecting stem disks at various heights from the stem base: 0 m, 0.2 m, 1.2 m, 3.2 m, and upwards at 2 m intervals throughout the length of the stem.

2.2.3 Tree-ring measurement and stem analysis

Widths of the tree rings were read along the long axis of the stem disk and the axis perpendicular to that. Surface of the stem disk was smoothed with a chisel where necessary; however, generally good growth of the sample trees did not necessitate prior smoothing of the stem disks with sanding devices.

For stem analysis, tree-ring widths of the stem cross-section were measured with a caliper at 0.1 mm accuracy for stem disks from trees with DBH greater than ca. 6 cm, and with a measuring microscope (Model PRM-D, Pika Seiko Co., Japan) at 0.01 mm accuracy for disks from trees with DBH smaller than about 6 cm.

The stem analysis program "stem4r.xls" (Miyaura 2015) was applied to the visually crossdated tree-ring data from a series of stem disks collected at various heights of a tree, and stem volume, stem diameter at breast height, total tree height, and annual stem volume increment were calculated. Finally, methods of the stand reconstruction technique (Osawa et al. 2000, 2005) were used to quantitatively reconstruct aboveground biomass, total stem volume, stem volume growth and stand density at the stand level.

2.2.4 Stand reconstruction technique

A detailed description of the concept and idea of the stand reconstruction technique is presented in Osawa et al. (2000). Osawa et al. (2005) also gave a summary of the technique and applied it to estimation of aboveground biomass, total stem volume, stem volume growth and stand density of even-aged *A. sachalinensis* stands. A short description of the stand reconstruction technique is presented in order to provide basic understanding of the method in the following discussion.

We denote v as stem volume without bark and w as aboveground tree mass (or stem volume) with bark. Also, DBH, tree height (H), v and w in the year of last tree census (2006 for Sugi; 2007 for Hinoki) are denoted as DBH^*, H^*, v^*, and w^*, respectively. Stem analysis is data obtained from the sample trees supply information on stem volume without bark at a given year in the past at fresh condition with appropriate correction between air-dried and fresh conditions. Census data provide observed information on DBH and tree height at different years and are used for validation of the estimates obtained by the stand reconstruction method. We can express the relationship between stem volume without bark at a given year in the past $v(t)$ and DBH^* and H^* as (Osawa et al. 2005),

$$v(t) = \alpha_2 \cdot (DBH^{*2} \cdot H^*)^{\beta_2} \qquad (1)$$

Eq. (1) states that $v(t)$ in the past can be estimated from DBH and tree height in 2006 for Sugi and 2007 for Hinoki, the most recent year of tree census. The parameter values of α_2 and β_2 change over time t. Stem analysis data were used to calculate these two parameter values at a given time in the past. Furthermore, the allometric relationship between w^* and v^* can be derived as,

$$w^* = \alpha_3 \cdot v^{*\beta_3} \qquad (2)$$

The parameters α_3 and β_3 are considered time independent in a given stand. Then, the above relationship applies also for a given year t,

$$w(t) = \alpha_3 \cdot v(t)^{\beta_3} \qquad (3)$$

By inserting Eq. (1) into Eq. (3), we have,

$$w(t) = \alpha_3 \alpha_2^{\beta_3} (DBH^{*2} \cdot H^*)^{\beta_2 \beta_3} \qquad (4)$$

The above equation allows us to estimate the stem volume or aboveground tree mass with bark of all trees in a stand at any year in the past from the most recent tree census data of 2006 for Sugi and 2007 for Hinoki.

Following cumulative functions are also defined to characterize stand statistics. We define $\varphi(w)$ as a frequency distribution function of w for a given stand at a given year (Hozumi 1971). Then, $Y(w)$, $N(w)$ and $M(w)$ are defined with the maximum value of stem size for this stand and year as (Hozumi 1971),

$$Y(w) = \int_{w}^{w_{max}} w \cdot \varphi(w)dw \quad (5)$$

$$N(w) = \int_{w}^{w_{max}} \varphi(w)dw \quad (6)$$

$$M(w) = Y(w)/N(w) \quad (7)$$

$Y(w)$ and $N(w)$ are cumulative aboveground biomass (or stem volume) of trees and the number of trees for those larger than or equal to w in a stand, respectively. $M(w)$ represents mean stem size for trees greater than or equal to the size w. Given that there is linearity between $M(w)$ and w with constants A and B (Hozumi 1971),

$$M(w) = A \cdot w + B, \quad (8)$$

the distribution function of stem size $\varphi(w)$ can be described as the beta-type distribution (Eq. (9)) with a constant C in Eq. (10) (Hozumi 1971),

$$\varphi(w) = C\{(A-1)w + B\}^{(2A-1)/(1-A)} \quad (9)$$

$$C = \frac{A}{Q} \cdot (\frac{\beta_1}{B})^{A/(1-A)}, \quad (10)$$

where, Q is plot area, and β_1 is a parameter satisfying the following relationship,

$$(Q \cdot N(w))^{(1-A)/A} = \alpha_1 \cdot w + \beta_1 \quad (11)$$

where α_1 is an additional constant (Hozumi, 1971).

Using the beta-type distribution function, total aboveground biomass ($Y(w_{min})$) and stand density ($N(w_{min})$) are expressed, respectively as (Hozumi 1971),

$$Y\left(w_{min}(t)\right) = \{A \cdot w_{min}(t) + B\} \cdot \frac{C}{A}\{(A-1) \cdot w_{min}(t) + B\}^{A/(1-A)} \tag{12}$$

$$N(w_{min}(t)) = \frac{C}{A}\{(A-1) \cdot w_{min}(t) + B\}^{A/(1-A)} \tag{13}$$

where $w_{\min}$ is the size of the smallest living tree in the stand.

Finally, the stem volume growth of a tree at year t, $\Delta v(t)$, was obtained from stem analysis data. The stem volume growth at year t was calculated using Eq. (14),

$$\Delta v(t) = v(t_2) - v(t_1) \tag{14}$$

where $v(t_2)$ and $v(t_1)$ represent stem volume without bark at years t_2 and t_1, respectively. Plus, additional information of stem volume without bark in the same year and Eq. (3) generate the following relationship,

$$\Delta v(t) = \alpha_4 \cdot w(t)^{\beta_4} \tag{15}$$

Parameters α_4 and β_4 are time-dependent and could be derived from fitting the Eq. (15) to the data logarithmically. Therefore, Eq. (15) can be applied to estimate stem volume growth at a stand level.

2.2.5 Testing predictions

The present paper discussed the effects of thinning events on the estimated stand variables by a stand reconstruction technique. A comparison was made of the reconstructed vs. observed values by calculating percentage error, defined as $(R-O)/O$, in which R and O stand for reconstructed and observed values, respectively. In addition, bootstrap method was used to calculate the 95% confidence limits of the estimated means by sampling tree data n times (n being the number of living stems) with replacement from the population of trees in the stand in 2006 for Sugi and 2007 for Hinoki, then repeating the process 1,000 times to estimate the 95% confidence interval (CI) (Efron 1979; Efron and Gong 1983).

2.3 Results and discussion

Both Sugi and Hinoki stands indicated that values of the estimates were generally underestimated for years before the thinning events based on the percentage error, in comparison to the observed values for all stand variables (Table 2. 3). For the Sugi stands, values of the estimated means tended to be underestimated for years before the thinning events (1980 and 1998) for plots A, B and C. Specifically, values of the estimated means were underestimated by 40%, 65%, and 15% for plots A, B and C, respectively, of the observed values of aboveground biomass, total stem volume, stem volume growth and stand density. The highly underestimated value of plot B (-60%) was probably caused by heavier thinning (73% thinning ratios by tree number in the years of both 1980 and 1998, Table 2. 1), in comparison to plots A and C. Although plot C received thinning ratio comparable to plots A and B, degrees of underestimation in the percentage error were less, in comparison to plots A and B. This is probably due to the large number of small trees in plot C compared to plots A and B (Appendix 2. 1). Although the thinning ratio by the number of trees were similar to the other two plots, the total amount of biomass or total stem volume removed in plot C in both thinning events (1980 and 1998) was not as much as that in plots A and B. For the control plot D, values of the percentage error of the estimates varied within ±20% of the observed values for aboveground biomass, total stem volume, and stem volume growth. Our results were in close agreement with those of Osawa et al. (2005) that the percentage error of the estimates can be generally trusted within ±17% of the observed values of the three variables from 1985 to 1998, except for stand density. In other words, our predictions from 1980 to 1998 encountered similar errors to those observed by Osawa et al. (2005), given that our control plot D and the Abies plots studied by Osawa et al. (2005) never experienced thinning. The estimates of stand density for plot D were generally reconstructed with reasonable accuracy (+5%). For the Hinoki stand, values of the percentage error of the estimates generally varied from -35% to

-74% of the observed values for all stand variables for years before the thinning events (1973, 1977 and 2003, Table 2. 2). The three thinning events caused similar underestimation to those in the Sugi stands. The combined results of the percentage error in Sugi and Hinoki stands suggested that thinning caused underestimation in the stand variables for years before the thinning events.

In addition to testing prediction accuracy, bootstrap method was used to estimate the 95% confidence intervals (C.I.) of the estimated means of the reconstructed stand variables. For aboveground biomass and total stem volume of Sugi stands, general lack of overlap between the estimated 95% C.I. of the mean of the reconstructed value and the observed value before the thinning operations in plots A and B suggested significant difference between the two estimates, thus, underestimation of the reconstructed values. In contrast, the estimates generally overlapped between them in plots C and D, showing that the predictions are reasonable. For aboveground biomass and total stem volume of the Hinoki stand, general lack of overlap was clearly illustrated in the years before the thinning events (1973, 1977 and 2003). The general overlap of the estimated 95% C.I. with the observed value in both Sugi and Hinoki stands in the years after the thinning events suggested that these two means were not different statistically (Fig. 2. 1 and 2. 2).

Stem volume growth of the Sugi stands showed similar patterns to the prediction of total stem volume. Generally non-overlap patterns between the 95% C.I. of the estimated means and the observed values before the thinning years were illustrated in plots A and B and general overlap between them was shown in plot C and partial overlap was shown in plot D. This is probably resulted from different stages in stand development. The non-overlap part (between 1979 and 1985) in plot D could be the early stage of stand development that the growth of tree size within these years was minimal (2.8 cm), in comparison to the overlapped part (between 1989 and 2006 = 4.7 cm). For the Hinoki stand, the general lack of overlap between the estimated 95% C.I. of the mean of the reconstructed value and the observed value before the thinning operations was reported (Fig. 2. 3). The results from the bootstrap of both Sugi and Hinoki stands suggested that general non-overlap patterns tended to occur before the thinning events, indicating underestimation of stem volume growth for the years before the thinning.

For stand density of Sugi stands, general lack of overlap patterns between the 95% C.I. of the estimated mean and the observed mean before the thinning years were illustrated in plot A, and general overlap between them was shown in plots B, C and D. The same pattern can be noticed in the stand density of the Hinoki stand. Generally non-overlapping pattern was shown in the years before the thinning events (Fig. 2. 4). The general overlap of the estimated 95% C.I. and the observed values in both Sugi and Hinoki stands in the years before the thinning suggested that the reconstructed values were generally underestimated.

Apart from testing the relationships between the observed and reconstructed values, the relationship between thinning ratio by basal area in 1998 and the percentage error of each stand variable in 1998, 1989, 1985, 1984, and 1982 for Sugi stands presented a different perspective on the effects of thinning on the estimated stand variables. For aboveground biomass and stem volume, the relationship between the thinning ratio by basal area and the percentage error was fairly significant, represented by $R^2 \geq 0.55$ for most of the years. This indicated that the greater the degree of thinnings in 1998, the greater the percentage error in the predictions of aboveground biomass and stem volume in the years before 1998. For stem volume growth, the relationships between the thinning ratio by basal area and the percentage error was weak, highlighted by $R^2 \leq 0.46$ for most of the years. For stand density, significant relationship between the degree of thinnings and the percentage error was manifested by $R^2 \geq 0.80$ for all years before the thinning operation in 1998. Overall, the relationship between the degree of thinning and the percentage error in Sugi stands further accentuated that the greater the thinning ratios by basal area, the greater the percentage error. In other words, when heavier thinnings occurred in particular forest stands, the errors in predicting the stand variables by the stand reconstruction technique were generally larger (Fig. 2. 5).

In a more specific assessment by examining differences in the individual years, the percentage error and bootstrap method clearly revealed a general trend of underestimated stand variables for the years before the thinning events (1980 and 1998 for Sugi; 1973, 1977 and 2003 for Hinoki). The present study did not consider the effects of the specific thinning methods on the predictions of forest stand variables. However, it should be worth considering in the future studies.

2.4 Conclusion

Effects of artificial thinning on the current form of the stand reconstruction technique generally showed underestimated stand variables for years before the thinning events; however, the errors were much smaller for years after the thinning events based on the results from the percentage error for both Sugi and Hinoki stands. The present analysis indicates that possible improvement could be obtained in the current form of the stand reconstruction technique if tree information that had lost by thinning operations can be incorporated into the analysis. Therefore, future work should consider using tree residuals (e.g. dead stems and/or decaying stumps) to test possibility in improving the stand reconstruction technique.

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Table 2. 1 Characteristics of the Japanese cedar stands and history of thinning events

Treatment plots	Plot areas (m^2)	Stand density in 1979 (No. of trees/ha)	Stand density in 2006 (No. of trees/ha)	Thinning ratio by tree number in 1980 (%) *	Thinning ratio by basal area in 1980 (%)	Thinning ratio by tree number in 1998 (%)	Thinning ratio by basal area in 1998 (%)
A	800	1663	675	24	12	44	33
B	700	1643	643	34	21	39	30
C	700	1643	686	45	28	20	13
D	600	1650	1267	Control	Control	Control	Control

* Calculation of thinning ratio by tree number in 1980: (numbers of thinned trees in 1980 * 100) / total number of trees existed in 1979

Table 2. 2 Characteristics of the Japanese cypress stand and history of thinning events

Plot area (m^2)	Planting density in 1953 (No. of stems/ha)	Thinning events	Number of thinned trees	Thinning ratio by tree numbers (%)	Thinning ratio by basal area (%)
450	3000	1973	22	18	4.04
		1977	40	40	14.39
		2003	20	34	20.27

Table 2. 3 Percentage error of the reconstructed values of aboveground biomass (AGB), total stem volume (SV), stem volume growth (SVG) and stand density (SD) for different years. Percentage error is defined as (R − O)/O, in which R and O stand for reconstructed and observed values, respectively

Species	Treatment plots	Year	AGB	SV	SVG	SD
Japanese cedar	A	2006	0.3	0.0	0.0	5.7
		1998	-26.9	-25.6	-11.3	-39.6
		1989	-31.7	-32.5	-27.9	-42.2
		1985	-34.6	-36.1	-34.2	-42.9
		1984	-35.4	-37.0	-34.5	-42.9
		1982	-36.4	-38.2	-36.7	-43.8
		1979	-48.2	-48.6	-48.4	-58.8
	B	2006	-1.2	0.0	0.0	-13.1
		1998	-37.3	-31.1	-26.0	-46.6
		1989	-52.1	-38.1	-38.6	-58.1
		1985	-61.5	-41.1	-42.0	-66.5
		1984	-62.2	-40.8	-43.8	-67.6
		1982	-66.1	-41.7	-43.4	-72.2
		1979	-73.0	-50.4	-50.5	-83.9
	C	2006	0.0	0.0	0.0	9.7
		1998	-8.5	-11.9	-7.5	-11.6
		1989	-3.5	-6.8	-4.3	-14.8
		1985	2.1	-6.4	-8.9	-14.4
		1984	-0.6	-4.9	-3.5	-14.4
		1982	3.6	-1.1	-1.1	-15.5
		1979	-7.3	-12.1	-17.3	-53.6
	D	2006	0.8	0.0	0.0	9.6
		1998	-5.4	-12.2	-10.3	1.9
		1989	-5.3	-15.0	-14.5	0.3
		1985	-6.2	-18.2	-18.9	4.7
		1984	-7.4	-19.8	-22.8	5.6
		1982	-7.7	-20.7	-20.7	0.6
		1979	-4.4	-19.9	-20.0	4.8
Japanese cypress		2007	-2.5	0.0	0.0	-2.9
		2003	-42.6	-38.9	-82.5	-37.5
		1997	-40.7	-38.2	-16.9	-38.6
		1992	-38.7	-37.6	-11.3	-39.4
		1983	-39.6	-42.2	-27.2	-41.7
		1977	-58.6	-61.8	-52.5	-66.5
		1973	-62.7	-66.2	-62.5	-74.0

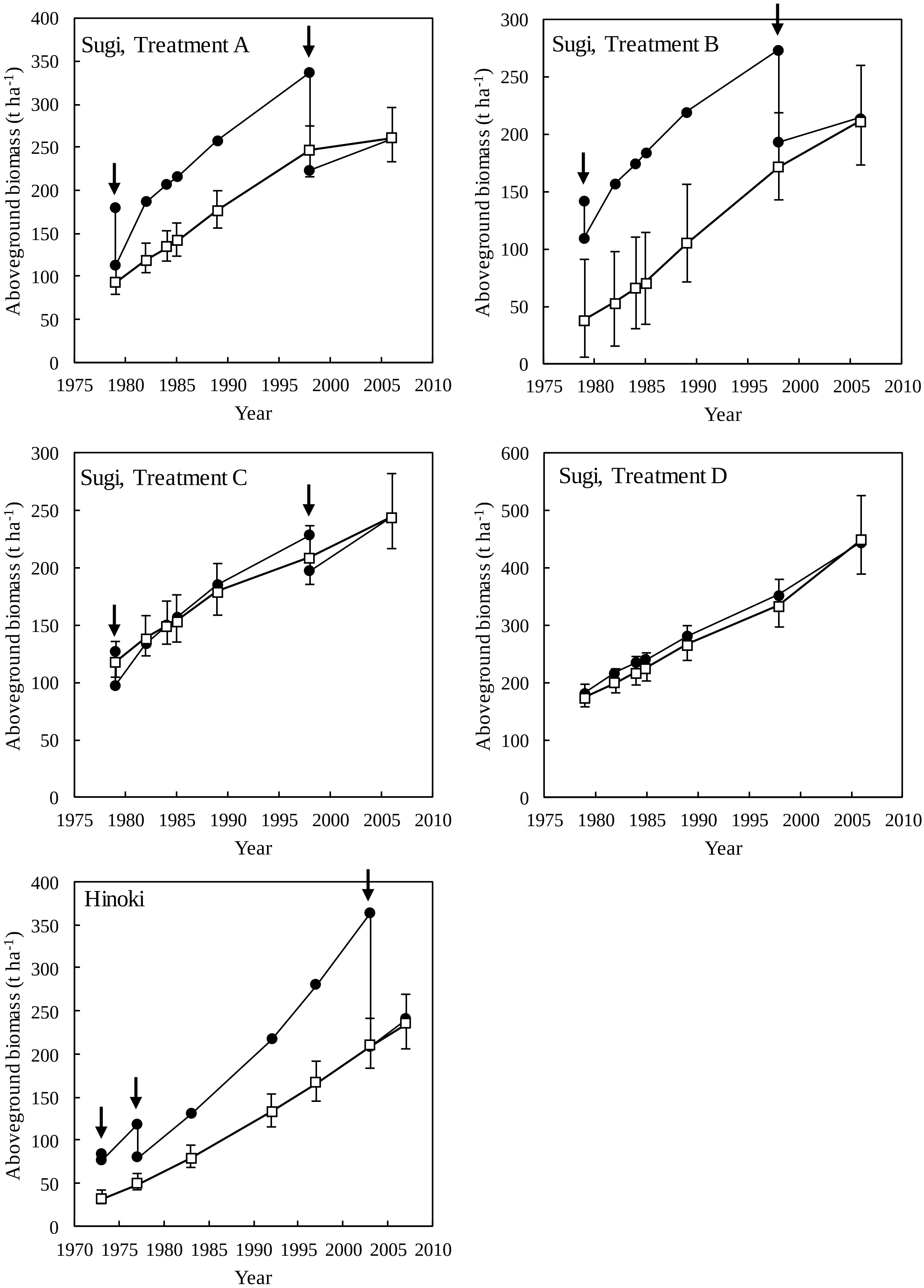


Fig. 2. 1 Relationship between reconstructed and observed values of aboveground biomass. □ and ● represent reconstructed values and observed values, respectively. Arrows indicate main years of thinning operations. Solid vertical bars indicate the upper and lower 95% confidence limits of the reconstructed values, based on the bootstrap method

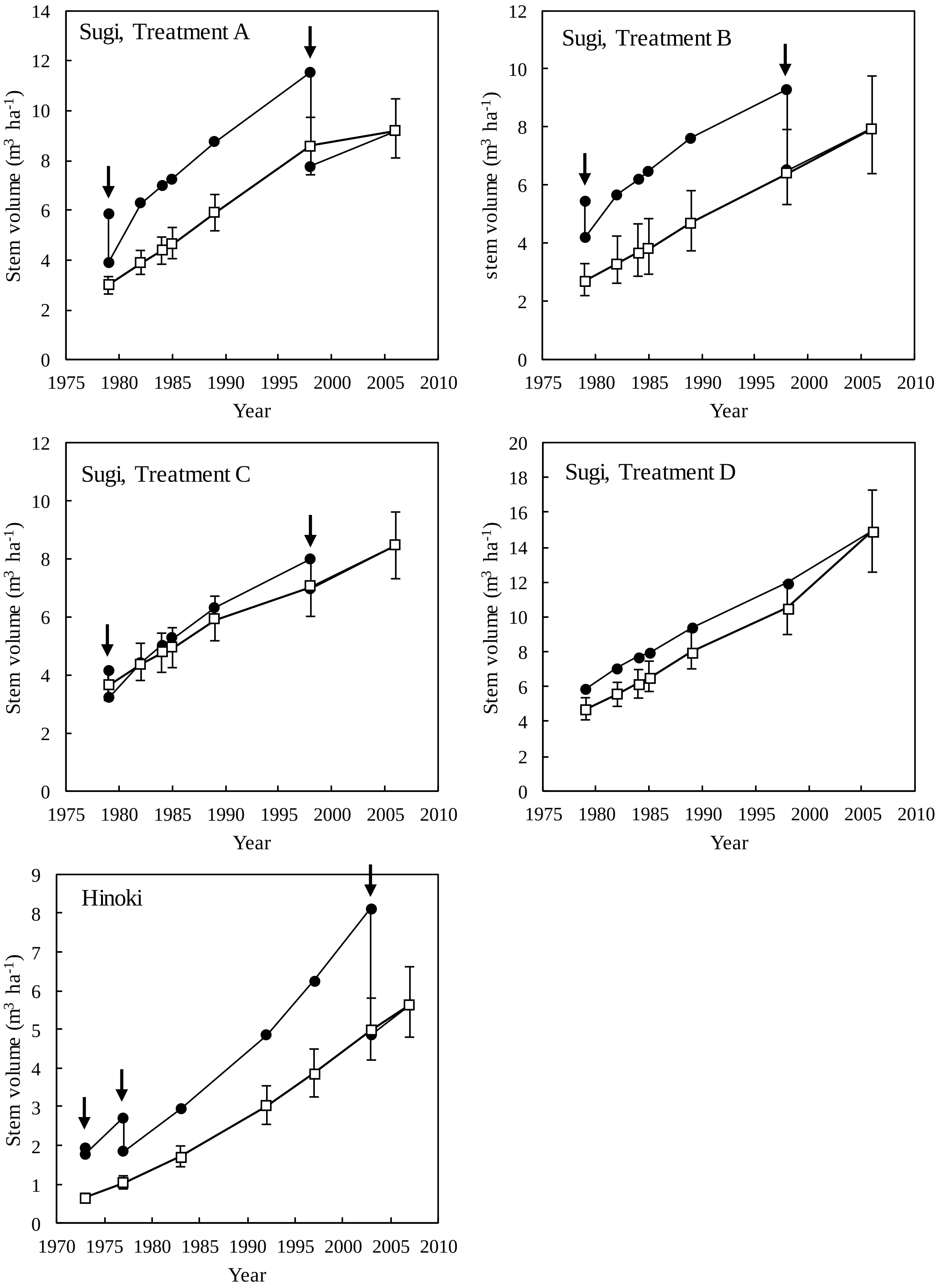


Fig. 2. 2 Relationship between reconstructed and observed values of total stem volume. □ and ● represent reconstructed values and observed values, respectively. Arrows indicate main years of thinning operations. Solid vertical bars indicate the upper and lower 95% confidence limits of the reconstructed values, based on the bootstrap method

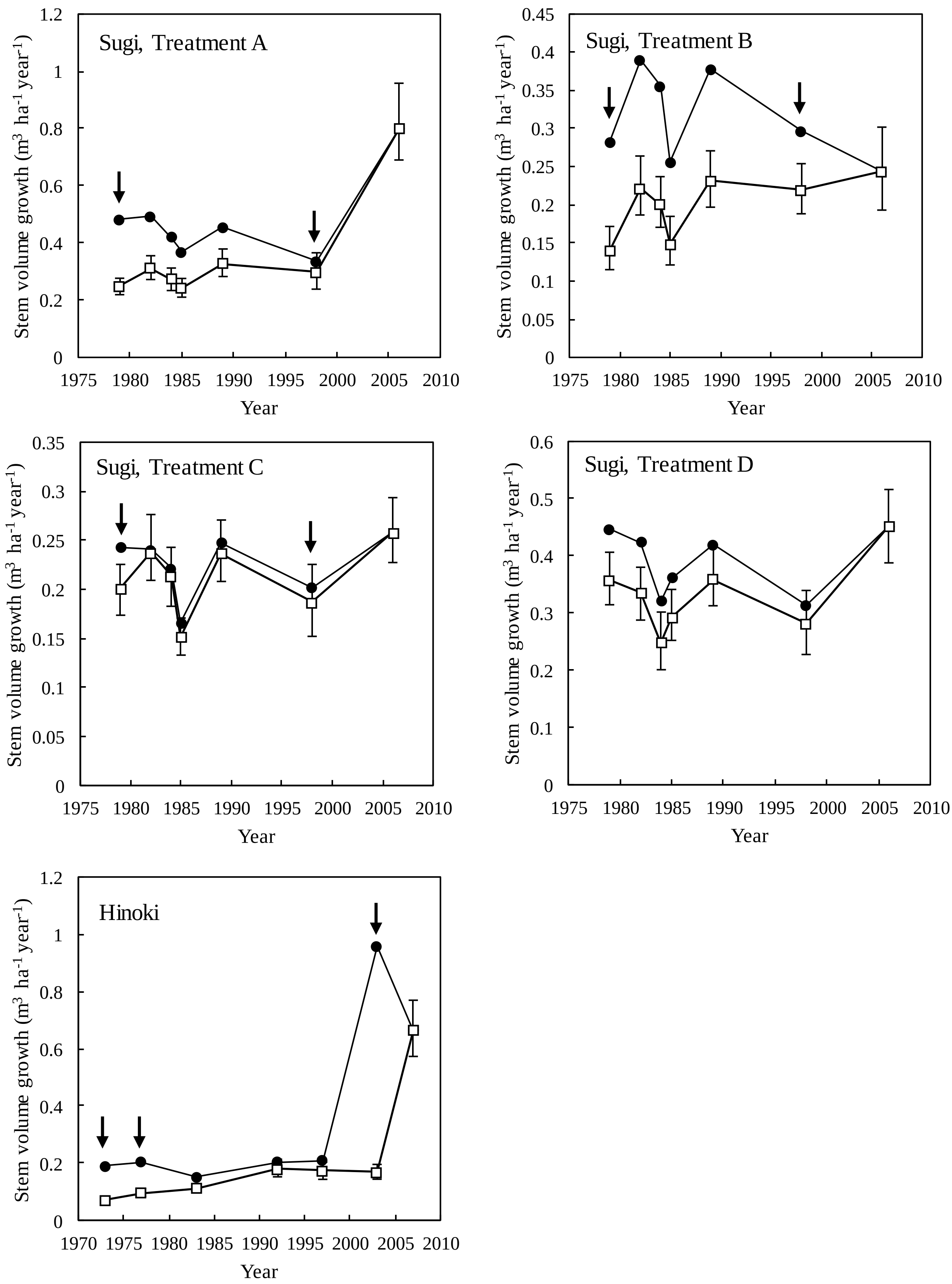


Fig. 2. 3 Relationship between reconstructed and observed values of stem volume growth. □ and ● represent reconstructed values and observed values, respectively. Arrows indicate main years of thinning operations. Solid vertical bars indicate the upper and lower 95% confidence limits of the reconstructed values, based on the bootstrap method

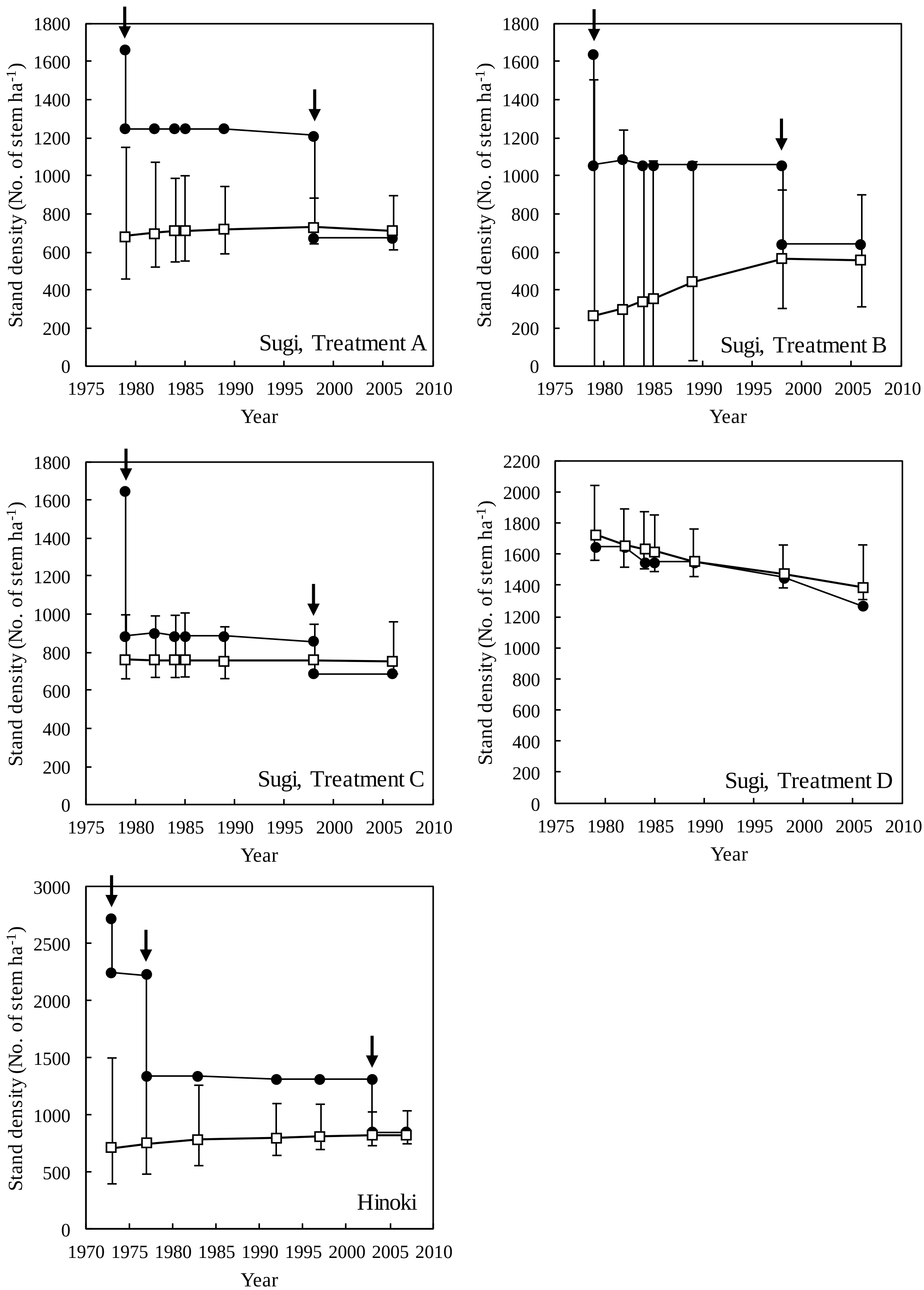


Fig. 2. 4 Relationship between reconstructed and observed values of stand density. □ and ● represent reconstructed values and observed values, respectively. Arrows indicate main years of thinning operations. Solid vertical bars indicate the upper and lower 95% confidence limits of the reconstructed values, based on the bootstrap method

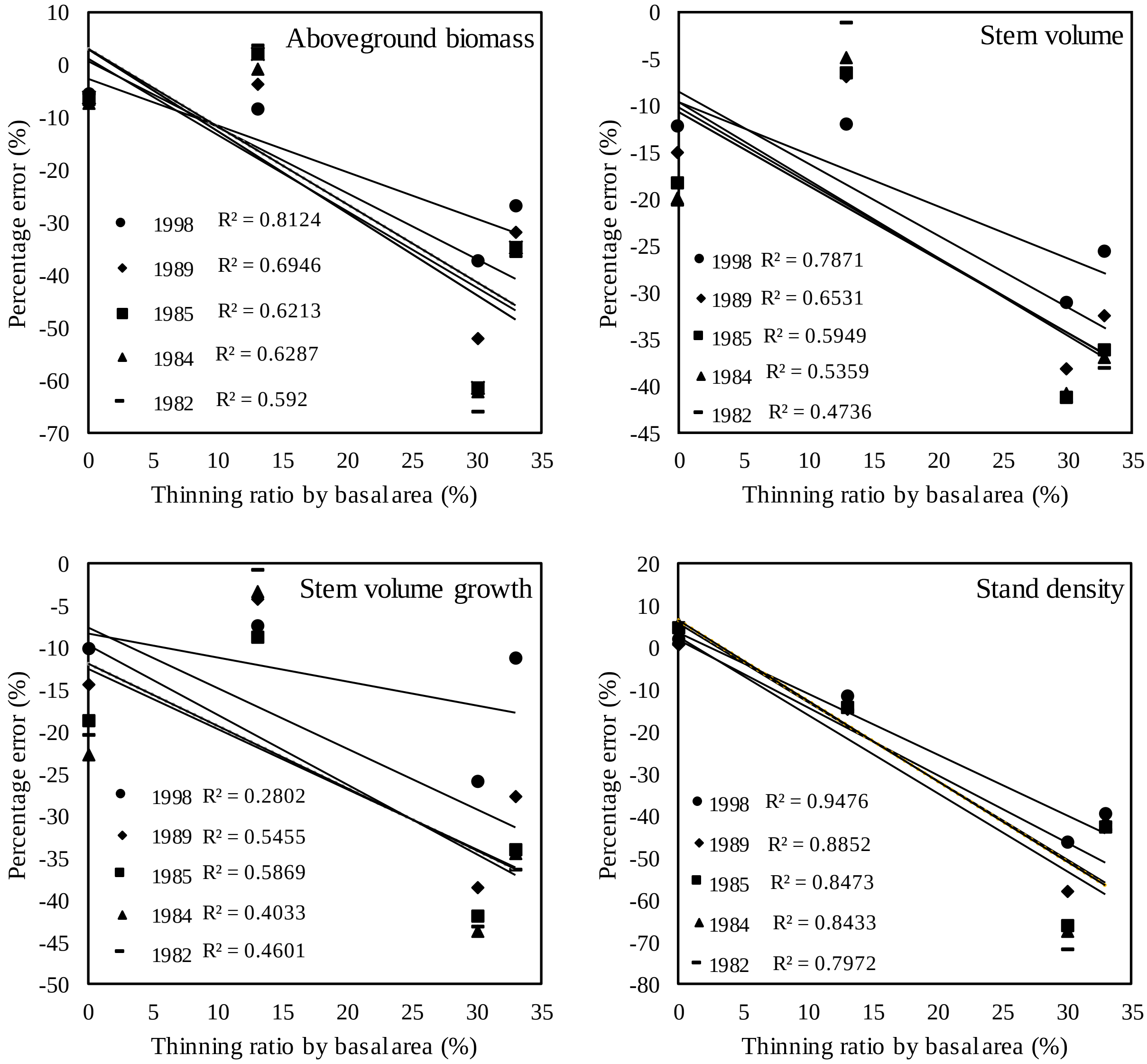
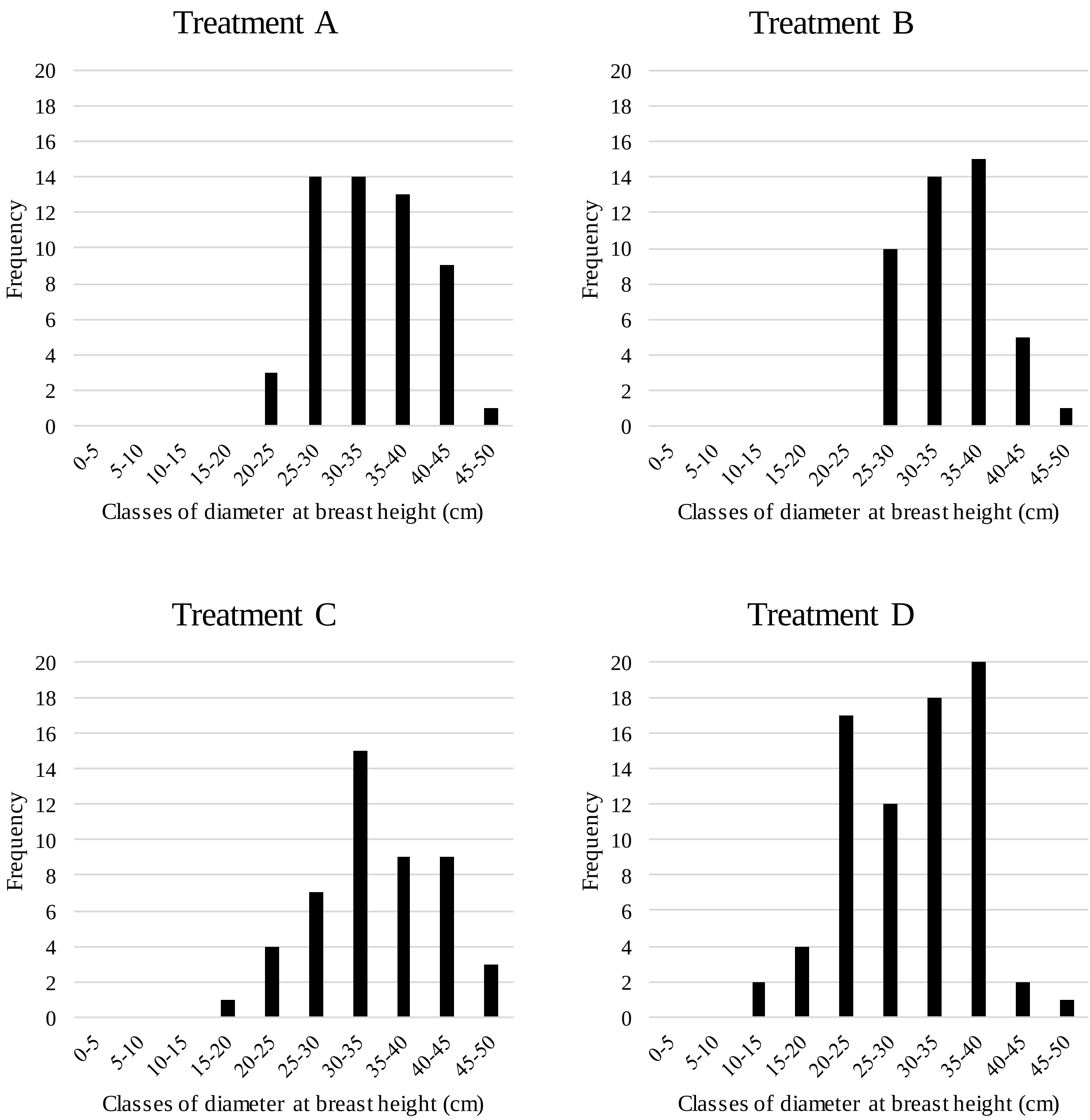


Fig. 2. 5 Relationship between thinning ratio by basal area in 1998 and percentage error of all treatment plots (A, B, C, D) for aboveground biomass, stem volume, stem volume growth and stand density in Sugi stands.

Appendix 2. 1: Distribution of diameter at breast height in 2006 from different plots in Japanese cedar stands



CHAPTER 3

Stand Reconstruction Technique: Thinning Effects on the Estimates of Stand Variables in Conifer Plantations in Hokkaido

Summary

This chapter explored the effects of thinning on the estimates of stand variables (aboveground biomass, total stem volume, stem volume growth and stand density) with a stand reconstruction technique in *Abies* and *Picea* plantations in Hokkaido. Thirty sample trees of *Abies sachalinensis*, *Picea jezoensis* and *Picea glehnii* were collected in six plantations of monospecific plots at Hitsujigaoka Experimental Forest in Hokkaido, Japan. Stem analysis data and census data gathered in 2013 from six stands were used to estimate the stand variables in the past by the stand reconstruction technique, and their accuracy was tested with the values calculated from the census data of the corresponding years. Results showed that percentage error of the estimated variables varied within ±20% of the observed values for the years after the thinning events. However, the estimates were underestimated (as large as 40%) for the years before the thinning operations. The 95% confidence intervals of the estimated means by the bootstrap method further emphasized the effects of thinning before the thinning operations, especially in *Abie sachalinensis*. The analysis suggests that thinnings and perhaps other disturbances cause underestimation in the stand reconstruction technique for years before the disturbance events. Therefore, results from the current stand reconstruction approaches must be interpreted with caution.

3.1 Introduction

Access to long-term data on changes in forest structure is rare and limited to certain geographical areas. Some regions where forestry has been the main industry have accumulated data for understanding stand growth and development. Other parts of the globe, however, still lack necessary data and methods in projecting forest stand development. Combining the demand in understanding the role of forest ecosystems in sequestering carbon and regulating global climate, accurate understanding of long-term changes in forest structure is important in forecasting stand growth and in assessing environmental effects on forests.

A combination of several methods has been practiced to retrieve long-term trends in forest growth and dynamics: tree-ring data, forest inventory data, long-term experiment, chronosequence of forest stands, forest stand reconstruction using stand legacies, and computer models. Tree-ring data (Mielikäinen and Nöjd 1996; Zang et al. 2012) derived from increment cores and stem disks can retrospectively extract valuable information about long-term growth at the individual tree level. However, absence of knowledge on historic growing conditions such as competitive status within the stand, insect outbreaks or silvicultural practices makes explanation of trends in individual tree growth and connection to stand, local, regional or global environmental changes unclear. The forest inventory data (Elfving and Tegnhammar 1996; Kauppi et al. 1992; Pretzsch 1996) produce representative information on tree and stand growth (Spiecker et al. 1996), but with few exceptions in northern Europe (Kauppi et al. 1992) and elsewhere, most inventory data date back to only two or three decades, which is rather short for examining long-term changes in forest structure (Tomppo et al. 2010). Long-term observation of experimental plots (Spurr et al. 1957; Mori and Osumi 1991) provide time series data probably shorter than tree ring data and less representative than inventories, but they can supply information on long-term performance both at tree and stand levels. Chronosequence of forest stands (Marks 1974; Saldarriaga et al. 1988; Aplet et al. 1989; Schulze et al. 1995;

Osawa et al. 2010) has been used to predict changes in forest structure and species composition over long time periods. However, the key assumption of this method that chosen stands in space are representative of various stages of development in time and have traced the same history may be untenable, particularly in reconstructing successional pathways (Johnson and Miyanishi 2008).

Stand reconstruction using stand legacies such as tree-rings, residual stumps, fallen logs, standing snags, branching patterns, stem scars and organic soil layers, have been used to infer successional development, disturbance history, changes in species composition and their spatial patterns, and changes in climate. This approach has been particularly successful in revealing the effect of natural disturbances on forest development (Henry and Swan 1974; Oliver and Stephens 1977; Oliver 1978; Clatterbuck and Hodges 1988; Taylor and Halpern 1991; Taylor 1993; Duncan and Stewart 1991; Savage 1991; Peter and Harrington 2010). However, this method often generates qualitative information of some stand characteristics rather than quantitative stand development, and requires substantial logistical effort in terms of data collection. The last approach is to use computer simulation models for understanding past forest dynamics and projecting further development. Gap model (Shugart 1984), growth-and-yield model (Newnham 1964), and carbon dynamics model (Kurz et al. 2008; 2009) are such examples. The advantage of this approach is the ability to provide quantitative estimates of future forest development and also to aid forest management decision-making. However, most simulation models are, by definition, abstract simplification of reality. The input parameters required to run the simulation are often not known and hence, assumed values are often used instead of the real data. True validation of the simulation results is often difficult also.

An alternative approach was proposed by Osawa et al. (2000) to deal with the question of quantitatively reconstructing long-term changes in stand development based mostly on samples and data available in the stand. It is referred to as a stand reconstruction technique, which uses information of present stand structure and tree-ring data of selected trees to reconstruct forest structure that existed long ago. Information of past stand structure is derived from tree-ring patterns. Osawa et al. (2005) applied the method to reconstruct aboveground biomass, total stem volume, stem volume growth, and stand density of even-aged monospecific stands and compared the estimates to the observed values in the past stand measurements. Fujii (2014) also used the technique to estimate long-term stand development of old plantations that experienced artificial thinning in the past and examined the accuracy of the predictions against the past observation. It has become apparent that thinnings or other disturbances may cause loss of information on individual trees in the stand, and may make it difficult to accurately reconstruct the tree size distribution that existed in the past. Yet, the effect of disturbances (e.g. artificial thinning) on accuracy of the stand reconstruction method has not been examined explicitly.

The purpose of this chapter was to investigate the effects of thinning on the estimated stand variables in the past by the method of stand reconstruction (Osawa et al. 2000, 2005) in the thinned conifer plantations of *Abies sachalinensis, Picea jezoensis* and *Picea glehnii*. In other words, the effects of thinning could be elucidated through the comparison of reconstructed values of aboveground biomass, total stem volume, total stem volume growth and stand density to those observed during previous stand measurements. We hypothesize that (1) the thinning causes underestimation of the stand variables with the stand reconstruction technique for the period before the thinning operation; (2) different levels of thinnings (or numbers of trees removed) generates different degrees of underestimation.

3.2 Materials and methods

3.2.1 Plot establishment and treatment

The study was conducted at Hitsujigaoka Experimental Forest (43°00'N 141°23'E) at Hokkaido, northern Japan at an altitude of approximately 150 m a.s.l. and on a flat terrain.

Mean annual temperature and annual precipitation are 7.5°C, and 952 mm, respectively (29-year means; Mizoguchi and Yamanoi 2015). General vegetation of the area is secondary deciduous broadleaf forest regenerated after wildfires in the late 19th century.

A series of even-aged monospecific plantations was established in 1973 (Sanada et al. 1995). Those included pairs of stands of *Abies sachalinensis* (Plots 8 and 9), *Picea jezoensis* (Plots 14 and 15) and *Picea glehnii* (Plots 18 and 19), each of which had a varying stand area between 153.6 and 306.7 m^2 (Osawa et al. 2005). The three species are distributed in northern Japan and in the surrounding maritime regions of northeast Asia. The secondary forest of the area was cleared, and burned before the plot establishment. Initial planting density of the plot was 3,900 stems per hectare. The plantations were maintained as a fertilization experiment. One block of the original planation consisted of 12 rows of 15 trees in each row for *A. sachalinensis*, 10 rows of 10 trees for both *P. jezoensis* and *P. glehnii*. Plots 9, 14, and 18 received NPK fertilizers annually starting in 1978, while plots 8, 15, and 19 did not receive any and were treated as control. The amount and timing of N, P, and K supplied to each fertilized plot were described in detail in Sanada et al. (1995). For *A. sachalinensis* (Plots 8 and 9), 15-22% of the trees in the plots were selected systematically without regard to tree size and quality and were thinned between 1998 and 2001 (Aizawa et al. 2012). Regarding *P. jezoensis* and *P. glehnii* (Plots 14 and 15, Plot 18 and 19), 15-25% of the trees, most of which were suppressed individuals, were thinned in 2003 (Table 3-1) (Tanaka et al. 2004; Aizawa et al. 2012). It is noted that examining the effects of fertilization on stand development was not the purpose of the present study. Rather, these stands were used to test the effectiveness of the stand reconstruction technique quantitatively when the stands developed with thinning treatments.

3.2.2 Stand measurement and stem disk collection

Tree height and DBH of all living stems were measured in 1978 when the stands were 5-years-old. Similar stand measurements were repeated at irregular intervals: years of censuses after 1978 varied depending on the study plot. DBH of the living trees in all plots was measured at approximately one to three-year intervals between 1970 and 2000, but measurement was done annually since the year 2000. The height of all living stems was measured annually between 1974 and 1988, then, in 1992 and 2010; but tree height measurement was done only for the selected trees in 1993, 1994, 1995 and 1998. Annual increment of tree height was also estimated from positions of branch whorls along a stem for the following years: 1974, 1975, 1976, and 1977 in 1978 census; 1979 in 1980 census; 1983 and 1984 in 1985 census; and 1989 and 1990 in 1991 census (Osawa et al. 2005). All living trees in the six plots were censused in November, 2013, and 30 sample trees (5 trees of various sizes per plot) were selected and felled for collecting stem disks at positions from the stem base: 0 m, 1.3 m, 3.3 m, and upwards at 2 m intervals throughout the length of the stem. These stem disks were brought to the laboratory, air-dried and sanded based on the method of sample preparation in dendrochronology. Stem disks were first sanded by a mechanical belt sander, then manually by sand paper, with progressively finer grades (80-1200 grits) (Stokes and Smiley 1968) to reveal their growth ring boundaries.

3.2.3 Tree-ring measurement, crossdating, and stem analysis

For stem analysis, tree-ring widths of stem cross-sections were measured at 0.01 mm accuracy with the "Velmex TA system" linear measurement device (Velmex Inc 2009) and the tree-ring measuring program "MeasureJ2X" (VoorTech 2008). Cross-sections were measured and counted from the outermost ring beginning with the year 2013 to the innermost ring. Every 10^{th} ring was marked with a single dot (Speer 2010). Visual crossdating was applied using CDendro (Cybis Elektronik 2010) to ascertain that each individual tree ring corresponds to a year of tree-ring production. Following visual crossdating, statistical accuracy of crossdating was checked using the computer program COFECHA (Holmes 1983; Grissino-Mayer 2001). When missing or absent rings presented, reinspection of tree rings was applied to ensure proper placement of a missing ring. The stem analysis program "stem4r.xls" (Miyaura 2015) was applied to the visually crossdated tree-ring data from a series of stem disks collected at various heights of a tree, and stem volume, stem diameter at breast height, total tree height, and annual stem volume increment were calculated. Finally, methods of stand reconstruction technique (Osawa et al. 2000, 2005) were employed to quantitatively reconstruct aboveground biomass, total stem volume, stem volume growth and stand density for the whole stand.

3.2.4 Stand reconstruction technique

The same stand reconstruction technique described at length in Chapter 2 was applied here for *Abies* and *Picea* plantations, and the last year of plot measurement is 2013.

3.2.5 Testing predictions

The goal of this chapter was to examine the effects of thinning on the estimated stand variables for even-aged plantations in the stand reconstruction technique. An approach in testing accuracy of the predictions is a comparison of the reconstructed vs. observed values by calculating percentage error, defined as $(R - O)/O$, in which R and O stand for reconstructed and observed values, respectively. Furthermore, bootstrap method was used to calculate the 95% confidence limits of the estimated means by sampling tree data n times (n being the number of living stems) with replacement from the population of trees in the stand in 2013, then repeating the process 1,000 times to estimate the 95% confidence interval (CI) (Efron 1979; Efron and Gong 1983).

3.3 Results and discussion

Values of the percentage error of the estimates generally varied within ±10% of the observed values of aboveground biomass, stem volume, stem volume growth, and stand density after the year 1998 for Abies and 2003 for Picea, except for some years when the error ascended to ±20% (Table 3-2). However, the percentage error grew larger to sometimes −40% before 1998 (for *Abies*) or before 2003 (for *Picea*). This suggested that the predictions of these variables can be trusted within ±10 to 20% only for the years after the times of the major thinning operations in 1998 (for *Abies*) or in 2003 (for *Picea*). If we focus on the estimates of stand density, it is generally reconstructed with reasonable accuracy (<±10%) after the thinning operations in 1998 for *Abies* plots 8 and 9, and in 2003 for *Picea* plots 14, 15, 18 and 19.

Regarding the percentage error, our results disagree with those of Osawa et al. (2005) that the percentage error of the estimates can be generally trusted within ±17% of observed values of three variables from 1985 to 1998, except for stand density. In other words, our predictions from 1985 to 1997 encountered larger errors (± 40%) than those from 1985 to 1998 (±17%) by Osawa et al. (2005). This difference is attributable to the fact that the stands used for the analysis (Plots 8 and 9) by Osawa et al. (2005) never experienced artificial thinning. Therefore, we observe that thinnings can affect accuracy of predictions in the stand reconstruction technique, especially for the years before the thinning operations.

To reaffirm our analyses and predictions, bootstrap method was used to estimate the 95% confidence intervals (C.I.) of the estimated means of the reconstructed stand variables. For aboveground biomass and stem volume, general lack of overlap between the estimated 95% C.I. of the mean of the reconstructed value (vertical bar in solid line) and the observed value before the thinning operations was shown in plots 8, 9, and 19, and general overlap between them was indicated in plots 14, 15 and 18. The general overlap of the estimated 95% C.I. and the observed value in plots 14, 15 and 18 in the years before the thinnings suggested that these two means were not different statistically (Fig. 3-1 and 3-2).

For stem volume growth, generally non-overlap patterns between the 95% C.I. of the mean (vertical bar in solid line) and the observed mean before the thinning years were illustrated in almost all plots. This suggested that the two means were different statistically.

For the estimates of stand density, nonoverlapping patterns of the estimated 95% C.I. of the mean in the reconstructed and observed values before the thinning operations (between

1998 and 2001 in *Abies* and 2003 in *Picea* stands) were shown in plots 8, 9, 18 and 19; but they overlapped in plots 14 and 15. The nonoverlapping patterns in *A. sachalinensis* and *P. glehnii* suggested that the differences were significant. In addition, the errors commonly loomed large for years before the thinning operations. A relatively young stand age is partly the cause of this error. Since the plantation was still relatively young, changes in tree number in the early years of stand development maybe small in plantations. In addition, trees were relatively small during the 1980s, making the predictions of stand density by the present approach more difficult. In comparison to the aboveground biomass, stem volume and stem volume growth, stand density is more difficult to be reconstructed (Osawa et al. 2005). For this reason, stand density estimation of our study did not reproduce the observed values well in most plots.

In general, the percentage error and the estimates of the 95% C.I. by the bootstrap method commonly suggested that moderate and larger errors of underestimation occurred in the years before the thinning operations in the four stand variables in all species (Table 3-2). According to the analysis, we confirmed both of our hypothesises that the thinning effects generated underestimated stand variables in the stand reconstruction technique and these effects be explained more clearly when thinning were heavier, especially in stand density.

3.4 Conclusion

The present analysis of the effects of thinning on the estimates of stand variables showed that thinning events tend to cause underestimation for years before the thinning operations; whereas, the errors tend to be much smaller for years after the thinnings according to the examination with the percentage error of estimated mean stand variables. In general, thinnings cause underestimation of stand variables in the current form of stand reconstruction technique. Understanding the effects of thinning in the stand reconstruction technique would allow us improve the technique. Including the thinned trees into the analysis by estimating their sizes may be a possibility, by which applicability of the technique may be further improved.

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Table 3. 1 Summary of stand statistics and thinning history

Species	Plot No.	Plot area (m^2)	Numbers of thinned trees	Thinned trees by basal area (m^2/ha)	Thinning history (by tree numbers)	Fertilization NPK
A. sachalinensis	8	306.7	34	10.62	15-22% (1998-2001)	No
	9	306.6	34	14.92	15-22% (1998-2001)	NPK
P. jezoensis	14	204.8	13	8.71	15-25% (2003)	NPK
	15	153.6	7	4.21	15-25% (2003)	No
P. glehnii	18	204.8	22	11.06	15-25% (2003)	NPK
	19	153.6	12	6.33	15-25% (2003)	No

Table 3. 2 Percentage error of the reconstructed values of aboveground biomass (AGB), total stem volume (SV), stem volume growth (SVG) and stand density (SD) for different years. Percentage error is defined as (R − O)/O, in which R and O stand for reconstructed and observed values, respectively

		Plot 8				**Plot 9**			
Species	Year	AGB	SV	SVG	SD	AGB	SV	SVG	SD
A. sachalinensis	2013	-2.0	-3.0	0.0	4.2	-1.5	-2.0	2.3	-0.5
	2010	-3.9	-4.2	1.1	-1.0	-3.7	-3.9	4.9	-8.7
	2006	-7.1	-7.2	-9.7	-8.1	-8.3	-8.4	-11.4	-18.1
	2003	-8.8	-8.5	-13.6	-11.8	-7.8	-7.9	-12.6	-17.0
	1997	-35.9	-37.3	-28.4	-43.6	-32.9	-32.9	-29.4	-44.8
	1993	-33.6	-36.9	-27.9	-46.9	-37.6	-38.4	-37.2	-43.8
	1988	-30.2	-26.8	-24.5	-51.6	-44.6	-45.1	-42.6	-44.2
		Plot 14				**Plot 15**			
P. jezoensis	2013	0.7	0.0	0.0	5.4	-1.6	0.0	0.0	1.1
	2010	0.9	-0.6	-1.0	6.6	1.0	2.2	2.5	2.3
	2006	-4.2	-7.0	-8.4	5.8	-5.5	-5.1	-6.7	3.3
	2003	-13.2	-19.3	-17.4	-14.6	-7.4	-7.6	-6.9	-10.7
	1997	-17.3	-25.9	-22.7	-15.3	-9.4	-10.1	-12.4	-28.1
	1993	-13.7	-22.7	-21.1	-15.0	-8.5	-8.1	-6.3	-31.5
	1988	6.0	-5.2	-6.6	-9.2	-4.6	-1.9	-7.1	-34.6
		Plot 18				**Plot 19**			
P. glehnii	2013	0.0	0.0	0.0	-0.9	0.0	0.0	0.0	-2.8
	2010	6.0	6.9	10.3	-0.2	-0.3	-3.6	-3.8	-3.8
	2006	2.8	3.0	3.3	1.9	-10.0	-12.0	-12.8	-5.2
	2003	-1.0	-1.0	-2.8	-31.0	-23.4	-25.1	-25.1	-27.7
	1997	-16.2	-12.6	-23.7	-37.8	-45.8	-44.9	-43.7	-38.0
	1993	-28.6	-22.4	-25.6	-40.0	-55.5	-52.9	-52.4	-40.1
	1988	-39.2	-28.0	-31.9	-50.6	-56.0	-51.3	-51.3	-40.6

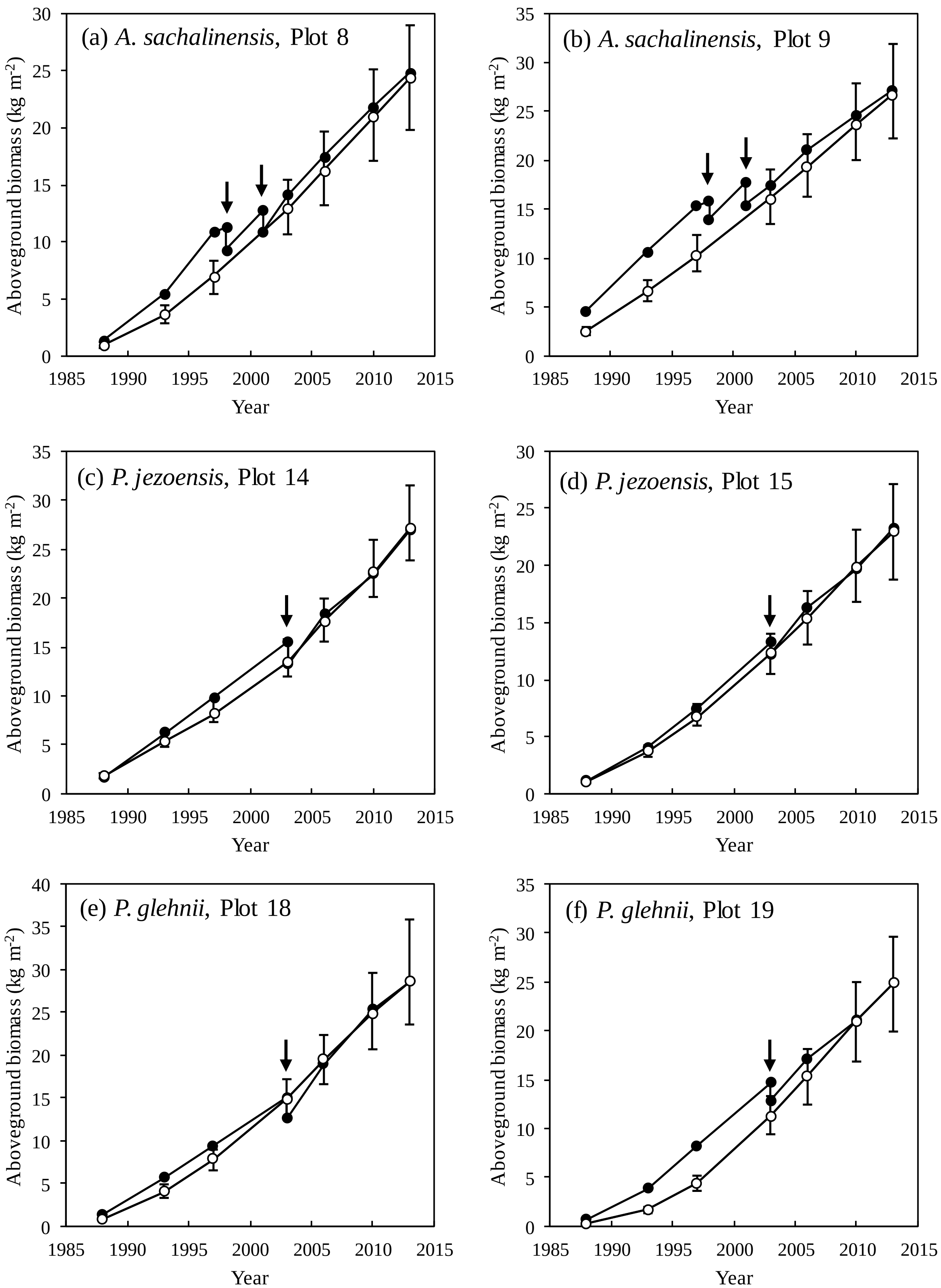

Fig. 3. 1 Relationships between reconstructed and observed values of aboveground biomass. ○ and ● represent reconstructed and observed values, respectively. Arrows indicate main years of thinning operations. Solid vertical bars indicate the upper and lower 95% confidence limits of the reconstructed values, based on the bootstrap method

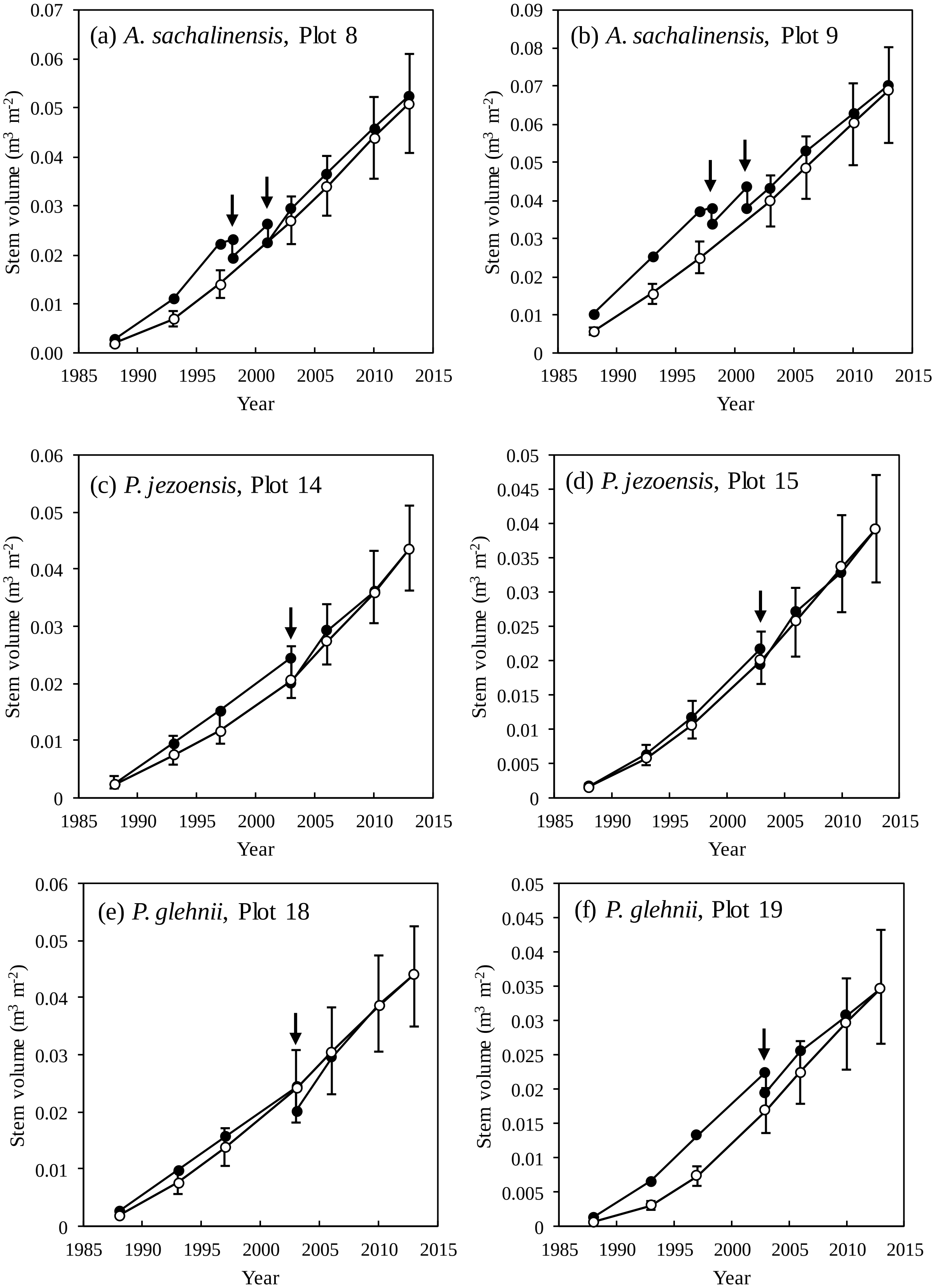

Fig. 3. 2 Relationships between reconstructed and observed values of total stem volume. ○ and ● represent reconstructed and observed values, respectively. Arrows indicate main years of thinning operations. Solid vertical bars indicate the upper and lower 95% confidence limits of the reconstructed values, based on the bootstrap method

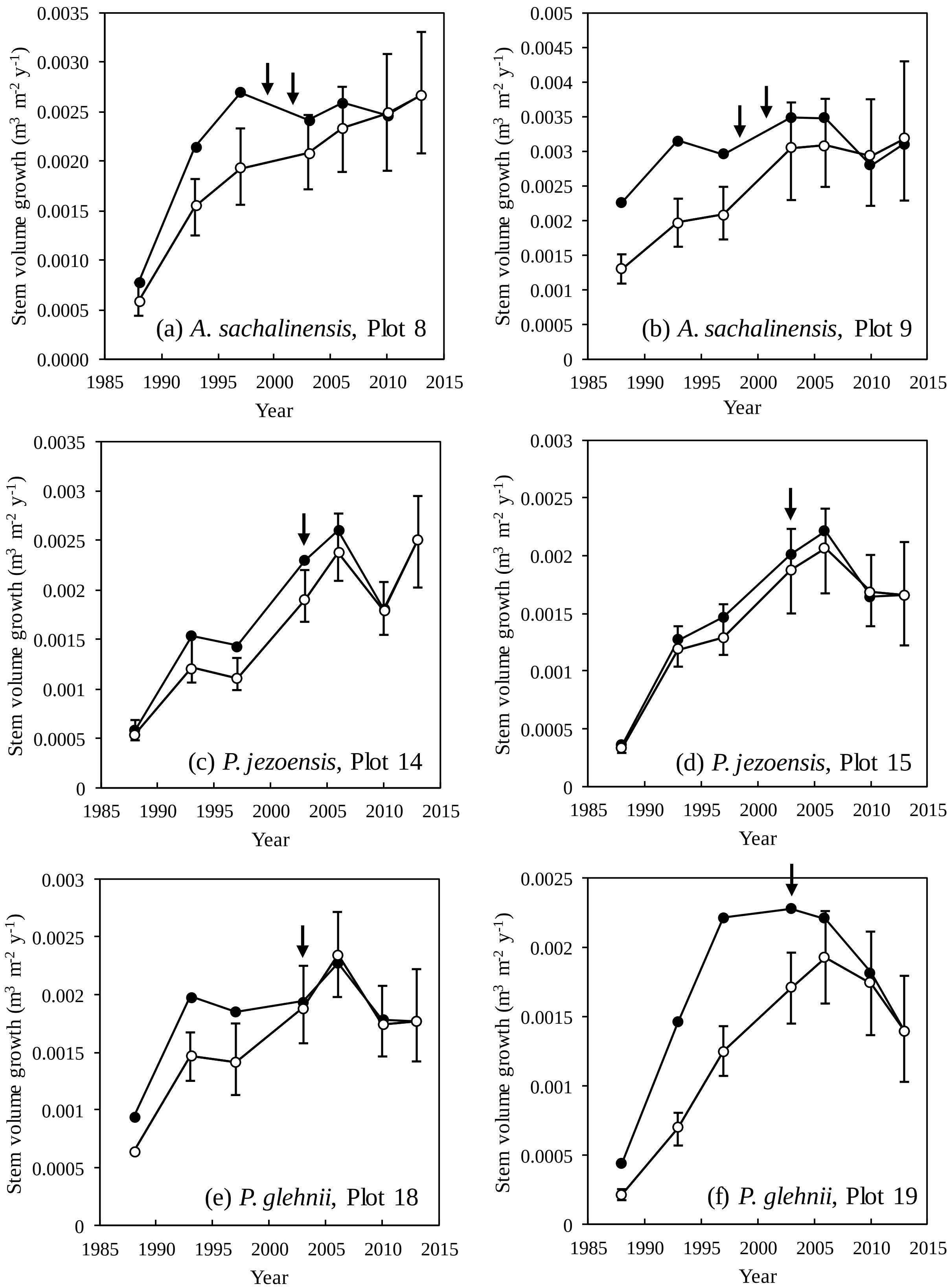

Fig. 3. 3 Relationships between reconstructed and observed values of stem volume growth. ○ and ● represent reconstructed and observed values, respectively. Arrows indicate main years of thinning operations. Solid vertical bars indicate the upper and lower 95% confidence limits of the reconstructed values, based on the bootstrap method

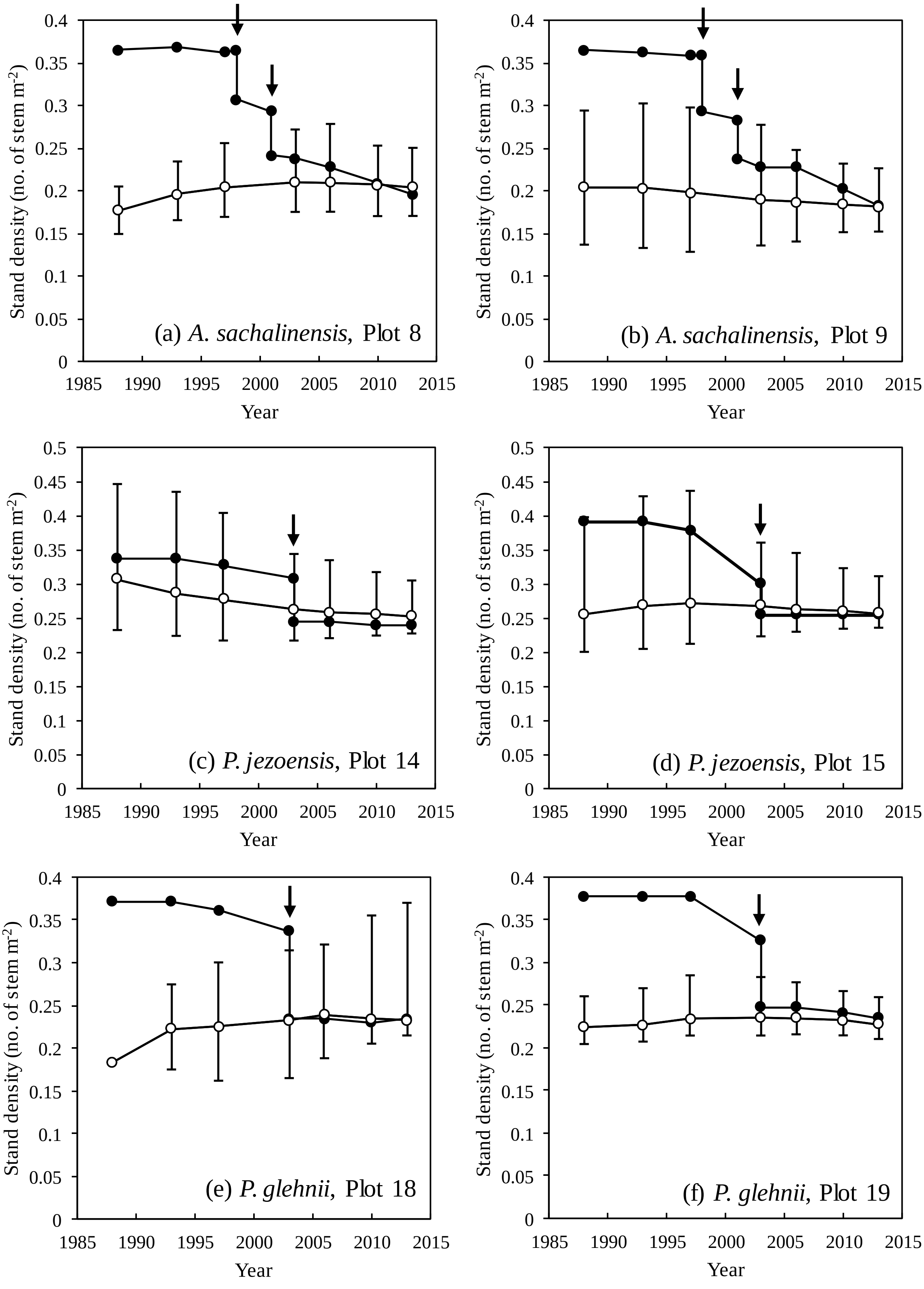

Fig. 3. 4 Relationships between reconstructed and observed values of stand density. ○ and ● represent reconstructed and observed values, respectively. Arrows indicate main years of thinning operations. Solid vertical bars indicate the upper and lower 95% confidence limits of the reconstructed values, based on the bootstrap method

CHAPTER 4

Correction of Stand Variable Estimates in a Stand Reconstruction Technique: Can Stump Information Improve the Predictions?

Summary

Information of thinned tree stumps was included in a stand reconstruction technique to test possible improvement in the estimates of stand variables (aboveground biomass, total stem volume, stem volume growth and stand density). Thirty sample trees and one hundred and sixty-eight stumps of *Abies sachalinensis*, *Picea jezoensis* and *Picea glehnii* were collected in six stands of pure tree species within the Hitsujigaoka Experimental Forest in Hokkaido, Japan. Stem analysis data and census data both gathered in 2013 from six stands were used to estimate stand variables in the past by the stand reconstruction technique, with and without the stump information. Then, these estimates were subsequently compared in terms of accuracy in prediction. In other words, the reconstructed values were statistically compared with the observed values obtained from the censuses between 1988 and 2013. Results showed that accuracy of the estimated variables can be improved by alleviating underestimation after adding old stumps. Without adding data from the stumps, percentage error of estimates of the stand variables varied within ±20% of the observed values for the years after 1997, and ±40% of the observed values for the years before 1997. By including the stumps, the percentage error of the estimates of the same stand variables generally fell within ±15%, and ±30% for the years after and before 1997, respectively. The 95% confidence intervals of the estimated means by the bootstrap method further reported that adding stumps does not always improve the prediction in stand density; but generally, improve the predictions in aboveground biomass, stem volume and stem volume growth. Overall, sudden changes in aboveground biomass and stand density through thinning operations were reproduced better, although the amount of improvement is sometimes minimal, by incorporating information of the stumps for all 3 species examined.

4.1 Introduction

Changes in the composition, structure and function of forest ecosystems may happen over long periods of time. Quantifying the changes in these components and processes would increase scientific and ecological understanding of forest development and their roles in regulating the climate system. Several methods have been employed to document and understand these changes: tree-ring analysis (e.g. Esper et al. 2012; Villalba et al. 2012; Zang et al. 2012), forest inventory data (e.g. Corona et al. 2011 Emily et al. 2010; Pretzsch 1996), chronosequences (e.g. Johnson and Miyanishi 2008; Marks 1974; Osawa et al. 2010), stand reconstruction (e.g. Henry and Swan 1974; Peter and Harrington 2010), and simulation model (e.g. Kurz et al. 2008, 2009; Shugart 1984).

Another method to deal with the question of quantitatively reconstructing long-term changes in stand development was developed by Osawa et al. (2000). It is referred to as a stand reconstruction technique, which uses information of present stand structure and tree-ring data of selected trees to reconstruct forest structure that existed long ago. Information of past stand structure is derived from tree-ring patterns. Osawa et al. (2005) applied the method to reconstruct aboveground biomass, total stem volume, stem volume growth, and stand density of even-aged monospecific stands and compared the estimates to the observed values in the past stand measurements. The same stands were used in Chapter 3, after they experienced thinnings, to evaluate the effect of thinning disturbance on estimates of those stand variables. The results highlighted that the effect of thinning causes underestimation in the stand reconstruction technique for years before the thinning operations. Therefore, it has become apparent that thinnings or other disturbances cause loss of information on individual trees in the stand and make it difficult to accurately reconstruct the tree size distribution that existed in the past. Yet, the effect of disturbances (e.g. artificial thinning) on accuracy of the stand reconstruction method has not been examined sufficiently. At the same time, accuracy of this method could potentially be improved by explicitly taking the effect of thinnings into account by including information retrieved from old stumps in the analysis from which the quantitative effect of thinnings can be accounted for. Usefulness of using information of the already dead stems in reconstructing stand structure in the past is also apparent from the study by Metsaranta et al. (2008) in which stand structure in the past was estimated from tree-ring and stem size data of both living and dead stems in forest stands.

The objective of this study was to test possible correction of the stand variables of stand reconstruction technique (Osawa et al. 2000, 2005) by including information of the thinned tree stumps found in the stands examined. The reconstructed values of aboveground biomass, total stem volume, stem volume growth and stand density were compared to those observed during previous stand measurements. In other words, the reconstructed values before and after adding the stump information will be compared to those observed from the census data. This kind of assessment has not been done previously and hence the results may lead to possible improvement in the estimates of stand variables in the stand reconstruction technique.

4.2 Materials and methods

4.2.1 Plot establishment and treatment

The study was conducted at Hitsujigaoka Experimental Forest (43°00'N 141°23'E) at Hokkaido, northern Japan at an altitude of approximately 150 m a.s.l. and on a flat terrain. Mean annual temperature and annual precipitation are 7.5°C, and 952 mm, respectively (29-year means; Mizoguchi and Yamanoi 2015). General vegetation of the area is secondary deciduous broadleaf forest regenerated after wildfires in the late 19th century.

The stands used in this analysis is the same as those examined in Chapter 3. A series of even-aged monospecific plantations was established in 1973 (Sanada et al. 1995). Those included pairs of stands of *Abies sachalinensis* (Plots 8 and 9), *Picea jezoensis* (Plots 14 and 15) and *Picea glehnii* (Plots 18 and 19), each of which had a varying stand area between 153.6 and 306.7 m^2 (Osawa et al. 2005). The three species are distributed in northern Japan and in the surrounding maritime regions of northeast Asia. The secondary forest of the area was cleared, and slash burned before the plot establishment. Initial planting density of the plot was 3,900 stems per hectare. The plantations were maintained as a fertilization experiment. One block of the original plantation consisted of 12 rows of 15 trees in each row for *A. sachalinensis*, 10 rows of 10 trees for both *P. jezoensis*, and *P. glehnii*. Plots 9, 14, and 18 received NPK fertilizers annually starting in 1978, while plots 8, 15, and 19 did not receive any and were treated as control. The amount and timing of N, P, and K supplied to each fertilized plot were described in detail in Sanada et al. (1995). For *A. sachalinensis* (Plots 8 and 9), 15-22% of the trees in the plots were selected systematically without regard to tree size and quality and were thinned between 1998 and 2001 (Aizawa et al. 2012). Regarding *P. jezoensis* and *P. glehnii* (Plots 14 and 15, Plot 18 and 19), 15-25% of the trees, most of which were suppressed individuals, were thinned in 2003 (Tanaka et al. 2004; Aizawa et al. 2012). It is noted that examining the effects of fertilization or thinning on stand development was not the purpose of the present study. Rather, these stands were used so that effectiveness of the stand reconstruction technique could be tested quantitatively when the stands developed with or without the thinning treatments.

4.2.2 Stand measurement and stem disk collection

Tree height and DBH of all living stems were measured in 1978 when the stands were 5-years-old. Similar stand measurements were repeated at irregular intervals: years of censuses after 1978 varied depending on the study plot. Tree height was measured for only the selected trees in 1995. DBH of the living trees in all plots has been measured annually since the year 2000, but measurement was done for only selected years from 1970s to 1990s. Annual increment of tree height was also estimated from positions of branch whorls along a stem for the following years; 1974, 1975, 1976, and 1977 in 1978 census; 1979 in 1980 census; 1983 and 1984 in 1985 census; and 1989 and 1990 in 1991 census (Osawa et al. 2005). All living trees in the selected six plots were censused in November, 2013, and 30 sample trees (5 trees of various sizes per plot) were selected and felled for collecting stem disks at 0 m, 1.3 m, 3.3 m, then at two-meter intervals throughout the length of the stem. Stem disks were first sanded by a mechanical belt sander, then manually by sand paper, with progressively finer grades sand paper (80-1200 grits) (Stokes and Smiley 1968) to reveal their growth ring boundaries.

4.2.3 Stump sampling protocol

We attempted to collect old stumps from the six plots in November 2015 from all trees that were cut by thinning operations in previous years. Trees were originally planted at grid points of approximately 1.6 m intervals. All trees were numbered systematically, and the history of stand treatment was known with specific cutting date for each thinned tree. Therefore, it was possible to determine for a given stump, the cutting date and tree size when harvested. When a stump was found, its diameter was measured with a diameter tape. If bark was absent or the perimeter of the stump was lost due to decay, it was noted. Then, the stump was cut carefully with a handsaw at the height of about 0.3 meter to yield a sample disk of 5-8 cm thickness. The stump samples were protected by covering them tightly with thin plastic film and then transported to the laboratory for analysis.

4.2.4 Decay classification

The rate and speed of the decomposition of stumps depend on a number of factors such as wood characteristics (tree species, dimensions), and site environmental factors (Radtke et al. 2004). The characterization of decay classes is usually based on the morphological features (e.g. presence or absence of bark) or hardness of the wood. Understanding the level of decay of the stumps allows rough estimate of the cutting date. According to Hunter (1990), stumps were classified with a system of five classes based on decay level with a five-point scale. This system is based on morphological wood features and other characteristics such as colour of wood and wood integrity. Since large numbers of the stumps have already disappeared and are gone, our study only covered classes 1 to 3. In the Hunter classification system, class 1 refers to stumps that have entire bark and the wood is hard with an intact structure and original colour. Class 2 falls onto stumps that the bark is partly disappeared. However, the wood is still firm and shows original colour. Class 3 is categorized as stumps that the bark is absent and the wood started to soften; however, the core is still firm. The colour started to fade away in this class. Fig. 4-1. shows some photographs of stump samples after sanding.

4.2.5 Treatment of stumps

The stump samples were dried at room temperature for about one week, then the decaying portions were fixed to prevent disintegration with ROTFIX®, epoxy resin developed specifically for decaying wood material. The epoxy resin was generously applied to the stump surface so that sufficient resin penetrated into the wood. When the decay was extensive, the stump sample was soaked in the epoxy resin. The samples were left to dry and harden for five to six hours. To reveal their growth rings, the stump samples were first sanded by a mechanical belt sander, then manually by sand paper, with progressively finer sand paper beginning with 240, 320, 400 grits, and ending with 800 grits (Stokes and Smiley 1968). It is noted that only the decay classes 1 and 2 of the stumps were sanded by the mechanical belt sander. The stumps of class 3 were sanded manually only with sand paper.

4.2.6 Tree-ring measurement, crossdating, and stem analysis

Tree-ring widths of stem samples of living trees and the stump samples were measured at 0.01 mm accuracy with the “Velmex TA system” linear measurement device (Velmex Inc 2009) and the tree-ring measuring program “MeasureJ2X” (VoorTech 2008). Tree rings of the stem disks from living trees were measured and counted from the outermost ring beginning with the year 2013 to the innermost ring. Every 10th ring was marked with a single dot (Speer 2010). However, the stump samples were measured differently from the living stem disks. Specifically, the starting point of measurement was from the pith, and the rings were read beginning with the relative year of 1 and continued to the outermost part of the rings. All tree-rings were visually cross-dated to match the corresponding years of tree-ring production. However, more systematic crossdating (such as the use of CDendro and COFECHA programs) was not practical due to relatively young tree age (ca. 40 years) in the present analysis. This may have caused some errors in the estimated cutting dates of the stumps. On the other hand, we assume that its effect on the estimated tree size in the past would be minimal if the decay of the stump was not extensive. The stem analysis program "stem4r.xls" was applied to the visually crossdated tree-ring data from a series of stem disks collected at various heights of a tree, and stem volume, stem diameter at breast height, total tree height, and annual stem volume increment were calculated (Miyaura 2015).

4.2.7 Stand reconstruction technique

The same stand reconstruction technique in Chapter 2 was applied here for *Abies* and *Picea* plantations, and the last year of plot measurement is 2013.

4.2.8 Incorporating stump information to the stand reconstruction technique

Stump diameter and tree-ring data provide sufficient information for adding to the stand reconstruction technique. Stumps of *A. sachalinensis*, *P. jezoensis*, and *P. glehnii* from the six plots were incorporated into the analysis with the original stand reconstruction method. Four main variables including aboveground biomass, stem volume with bark, stem volume growth and stand density were estimated with the added information of the stumps in the stand reconstruction technique. To estimate these variables, we first estimated DBH, stem volume without bark, stem volume with bark, and aboveground biomass of a tree from the stump sample. Then, stem volume, stem volume growth, aboveground biomass and stand density at the stand level and before the thinning were reconstructed by adding quantities of the trees estimated from the stumps into the stand reconstruction calculation for the years when the tree in question was alive. Methods for estimating several tree variables (DBH, total tree height, stem volume with bark and aboveground biomass) from the thinned tree stumps were described in the following.

Diameter at breast height (DBH): DBH of a thinned tree at the time of thinning was estimated from the measurement of stump diameter, $D_{0.3}$, and a quantitative relationship between DBH and $D_{0.3}$:

$$DBH = \alpha_5 + \beta_5 \cdot D_{0.3} \quad (16)$$

where α_5 and β_5 are time independent parameters that were determined from the trees used in stem analysis. The R^2 values for *A. sachalinensis, P. jezoensis,* and *P. glehnii* are 0.97, 098, and 0.98, respectively.

Stem volume with bark: Stem volume with bark at fresh condition, W(m^3), was estimated from DBH with bark at fresh condition with an allometric function as,

$$W = \alpha_6 \cdot DBH^{\beta_6} \quad (17)$$

where values of the time-dependent parameters α_6 and β_6 were evaluated by fitting a linear relationship to the log-transformed (base 10) form of Eq. (17). Stem analysis supplied data of stem volume and DBH without bark at air-dried condition for different years. DBH with bark at fresh condition was calculated as the without-bark DBH multiplied by 1.0331, 1.0387, and 1.0278 (R^2 = 0.99 for all species, n = 10) for *A. Sachalinensis*, *P. jezoensis*, and *P. glehnii*, respectively. Stem volume with bark at fresh condition was calculated similarly as without bark stem volume at air-dried condition multiplied by 1.043, 1.070, and 1.091 (R^2 = 0.99 for all species, n = 10) for *A. Sachalinensis, P. jezoensis*, and *P. glehnii*, respectively.

Stem volume growth: Eq. (15) also enables us to estimate stem volume growth of a tree from the stumps with information of the estimated stem volume without bark (v) and Eq. (3) in Chapter 2. Parameters α_4 and β_4 vary over time.

Aboveground biomass: Eqs. (2) and (3) in Chapter 2 allow us to estimate aboveground mass at any time in the past, in which aboveground mass was estimated from the stem volume. Stem volume of a tree when harvested was derived from size of the stump at any time in the past.

Stand density: Stand density that incorporated the thinned trees was estimated by adding the number of stumps in each plot assuming that those trees were living just before they were cut at a given year in the past.

4.2.9 Testing predictions

A method in testing improvement of the predictions is a comparison of the reconstructed vs. observed values by calculating percentage error, defined as $(R - O)/O$, in which R and O stand for reconstructed and observed values, respectively. In addition, bootstrap method was used to calculate the 95% confidence limits of the estimated means by sampling tree data n times (n being the number of living stems) with replacement from the population of trees in the stand in 2013, then repeating the process 1,000 times to estimate the 95% confidence interval (CI) (Efron 1979; Efron and Gong 1983).

4.3 Results and discussion

The present study attempted to answer the question whether adding the stumps into the original stand reconstruction technique could yield better predictions of long-term stand development for even-aged plantations. In the following, we discussed the stand reconstruction technique without adding the stumps, followed by that incorporating the stump information.

Without adding the stump information, values of the percentage error of the estimates generally varied within ±10% of the observed values of aboveground biomass, stem volume, stem volume growth, and stand density after the year 2003, except for some years that the error ascended to ±20%. However, the percentage error grew larger sometimes to ±40% before 1997 (for *Abies*) or before 2003 (for *Picea*). This suggested that the predictions of these variables can be trusted within ±10 to 20% only for the years after the major thinning operations in 1998 and

2001 (for *Abies*) or in 2003 (for *Picea*). If we focus on the estimates of stand density, it is generally reconstructed with reasonable accuracy (<± 15%) after the thinning operations of 1998 and 2001 for *Abies* plots 8 and 9, and of 2003 for *Picea* plots 14, 15, 18 and 19. Our results were in contradiction with those of Osawa et al. (2005) that the percentage error of the estimates can be generally trusted within ±17% of observed values of three variables from 1985 to 1998, except for stand density. In other words, our predictions from 1985 to 1997 encountered larger errors (± 40%) than those from 1985 to 1998 (±17%) by Osawa et al. (2005). This difference is attributable to the fact that the stands used for the analysis (Plots 8 and 9) by Osawa et al. (2005) never experienced thinning by the time of their study.

When the stump information was integrated into the analysis, our result indicated that values of the percentage error of aboveground biomass, total stem volume, stem volume growth and stand density generally decreased to less than ±15% (as opposed to ±20% without adding the stumps) of the observed values in any year after the thinning operations (i.e. 1998 and 2001 in *Abies* stands and 2003 in *Picea* stands), indicating that including the stumps slightly improved the predictions. For the years before 1997, the values of the percentage error generally descended to ±30% (as opposed to ±40% without the stumps) (Table 4-1). Overall, our results of percentage error suggested that adding the stump information showed small improvement of predictions in most plots, particularly for years before the thinnings.

To reaffirm our predictions, bootstrap method was used to estimate the 95% confidence intervals (C.I.) of the estimated means of reconstructed values with and without the stump information. For aboveground biomass and stem volume without adding stumps, general lack of overlap between the estimated 95% C.I. of the mean of the reconstructed value (vertical bar in broken line) and the observed value before thinning operations was shown in plots 8, 9, 18, and 19. In contrast, general overlap between them was indicated in plots 14, and 15. The general overlap of the estimated 95% C.I. and the observed value in plots 14 and 15 in the year before the thinnings suggested that these two means, without adding stumps, were not different statistically (Fig. 4-2 and 4-3). After including the stump information, the overlap between the 95% C.I. of the reconstructed values (vertical bar in solid line) and the observed values for aboveground biomass and stem volume was reported in plots 8, 18 and 19. This suggested that adding stumps can improve the predictions in these three plots in contrast to those without adding stumps. Overall, after adding stumps, significant improvement of the prediction could be seen clearly in *P. glehnii* (especially plot 19), in comparison to *A. sachalienensis* and *P. jezoensis*. This is probably due to the slow decay rate/speed of the *P. glehnii* stumps which depends on a number of factors such as tree species, dimensions (tree size), and site environmental factors (Radtke et al. 2004). According to Sakai et al. (2008), stumps of *A. sachalinensis* and *P. glehnii*, which are planted in a relatively cool region, tend to decay slower than other coniferous tree species. In our study, we confirmed that *P. glehnii* decayed slower than the other two species since the number of missing stumps were greater in *A. sachalinensis* and *P. jezoensis* (20 missing stumps in each species), but smaller in *P. glehnii* (13 missing stumps). In other words, our study reported that the stumps of tree species with slower decay rate can improve estimates of the stand variables of the stand reconstruction technique better than those with faster decay rate. However, our study showed negative correlation between tree size and decay rate, which is contrary to the general notion that tree with larger diameter decomposes more slowly than smaller ones (Harmon et al. 1986; Frangi et al. 1997). The mean stump diameters of *A. sachalinensis*, *P. jezoensis*, and *P. glehnii* are 12.26 cm, 14.16 cm, and 11.18 cm, respectively.

For stem volume growth without including stumps, generally non-overlap patterns between the 95% C.I. of the mean (vertical bar in broken line) and the observed mean before the thinnings were illustrated in almost all plots. This suggested that the two means were different, statistically. After adding the stump information, however, improvement in predictions, indicated by generally overlapping patterns, could be seen in plots 8, 14 and 18. This suggested that including stumps could improve the predictions in these three plots, but not those in plots 9, 15, and 19 (Fig. 4-4).

For the estimates of stand density without stumps, nonoverlapping patterns of the estimated 95% C.I. of the mean in the reconstructed and observed values before the thinning operations (1998 and 2001 in *Abies* and 2003 in *Picea* stands) were displayed in plots 8, 9, 18 and 19; but their overlap in plots 14 and 15. The nonoverlapping patterns in *A. sachalinensis* and *P. glehnii* suggested that the differences were significant. Even though stumps were included, the improvement was only minimal in *A. sachalinensis* and *P. glehnii* plots and this was shown by the lack of overlap patterns of the confidence limits (Fig. 4-5). In addition, the errors commonly loomed large for years before the thinning operations. A relatively young stand age is partly the cause of this error. Since the plantation is still young, changes in tree number in the early years of stand development maybe small. In addition, trees were relatively small during the 1980s, making the predictions of stand density more difficult. Compared to the aboveground biomass, stem volume and stem volume growth, stand density is more difficult to reconstruct (Osawa et al. 2005) and even after adding stump information, the reconstructed and observed values still do not agree well. For this reason, stand density estimation of our study did not reproduce the observed values well in most plots.

Results of the percentage error and the estimates of the 95% C.I. by the bootstrap method suggested moderate to large errors in estimating aboveground biomass, total stem volume, stem volume growth, and stand density in some plots. Additional error could be due to the error associated with the cutting dates of the stumps inferred from the tree-ring analysis. In our study, some stumps did not show sufficiently clear rings. More importantly, majority of the stump samples did not have many rings for their young age, and it prevented a systematic crossdating. Furthermore, growth of some stumps showed poor circuit uniformity, which refers to the tree rings concentrating around the middle of the cross-section of a stem. And circuit uniformity is required for successful crossdating (Speer 2010). In our study, a large number of our stump samples falls into class 3 of decay classification system, indicating extensive decay and barkless condition. Therefore, error in the estimates of cutting date of the stumps probably occurred. We discovered that the estimated cutting dates is close to the actual cutting dates for stumps categorized as class 1, and the error in cutting dates was as much as 4 years. However, for the class 2 and 3 stumps, the estimated and actual years of cut differed greatly (up to 20 years) (Table 4-2).

Errors in estimating cutting dates also led to errors in estimating DBH from the stumps, which was the main variable in estimating stem volume with bark and stem mass with bark. This may have resulted in underestimation or overestimation of the stand variables when the stumps were added to the original stand reconstruction technique. It is noted that estimating DBH, stem volume with bark and stem mass with bark from the stump samples are intractable, when most of the stump samples fall onto the class 3 decay classification system.

4.4 Conclusion

The present analysis of taking into account stump information in the structural stand reconstruction in thinned plantations showed that the method could be applied to improve estimates of the aboveground biomass, total stem volume and stem volume growth; but the estimates of stand density do not always improve for the periods before the thinning operations even after adding the stump information for estimation. The improvement can be small or unclear when the level of the thinning is minor. However, inclusion of stump information in the stand reconstruction technique generally improves the levels of the relative error of the estimates and is recommended. Successful collection of appropriate stumps and/or dead stems, which is related to quality of the wood material (whether it is undecayed or decaying), would further improve the predictions. Caution should be applied when reading and crossdating tree rings from the stumps originated from a younger plantation. The improvement by adding the stumps in the stand reconstruction technique could probably be seen clearly, given that the level of thinning is larger and the decay rate of stumps is slower. Overall, taking into account of stumps would widen applicability of the original stand reconstruction technique and provide further insights into analysis of long-term structural changes in forest stands.

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Table 4. 1 Percentage error of the reconstructed values of aboveground biomass (AGB), total stem volume (SV), stem volume growth (SVG) and stand density (SD) for different years. Percentage error is defined as (R − O)/O, in which R and O stand for reconstructed and observed values, respectively

			With stumps (*R-O*)/*O*				Without stumps (*R-O*)/*O*			
Species	Plot	Year	AGB	SV	SVG	SD	AGB	SV	SVG	SD
A. sachalinensis	8	2013	-2.0	-3.0	0.0	4.2	-2.0	-3.0	0.0	4.2
		2010	-3.9	-4.2	1.1	-1.0	-3.9	-4.2	1.1	-1.0
		2006	-7.1	-7.2	-9.7	-8.1	-7.1	-7.2	-9.7	-8.1
		2003	-8.8	-8.5	-13.6	-11.8	-8.8	-8.5	-13.6	-11.8
		1997	-26.0	-25.7	-16.4	-33.7	-35.9	-37.3	-28.4	-43.6
		1993	-16.5	-18.9	-9.1	-29.2	-33.6	-36.9	-27.9	-46.9
		1988	-1.4	9.8	0.6	-26.6	-30.2	-26.8	-24.5	-51.6
A. sachalinensis	9	2013	-1.5	-2.0	2.3	-0.5	-1.5	-2.0	2.3	-0.5
		2010	-3.7	-3.9	4.9	-8.7	-3.7	-3.9	4.9	-8.7
		2006	-8.3	-8.4	-11.4	-18.1	-8.3	-8.4	-11.4	-18.1
		2003	-7.8	-7.9	-12.6	-17.0	-7.8	-7.9	-12.6	-17.0
		1997	-27.0	-27.1	-24.6	-37.5	-32.9	-32.9	-29.4	-44.8
		1993	-26.7	-27.8	-25.8	-28.4	-37.6	-38.4	-37.2	-43.8
		1988	-26.0	-26.6	-23.8	-21.8	-44.6	-45.1	-42.6	-44.2
P. jezoensis	14	2013	0.7	0.0	0.0	5.4	0.7	0.0	0.0	5.4
		2010	0.9	-0.6	-1.0	6.6	0.9	-0.6	-1.0	6.6
		2006	-4.2	-6.5	-8.4	5.8	-4.2	-7.0	-8.4	5.8
		2003	-13.2	-16.2	-17.4	-14.6	-13.2	-19.3	-17.4	-14.6
		1997	-5.3	-10.9	-15.5	-7.9	-17.3	-25.9	-22.7	-15.3
		1993	1.8	-5.7	-12.3	-6.3	-13.7	-22.7	-21.1	-15.0
		1988	42.4	30.3	10.0	6.8	6.0	-5.2	-6.6	-9.2
P. jezoensis	15	2013	-1.6	0.0	0.0	1.1	-1.6	0.0	0.0	1.1
		2010	1.0	2.2	2.5	2.3	1.0	2.2	2.5	2.3
		2006	-5.5	-5.1	-6.7	3.3	-5.5	-5.1	-6.7	3.3
		2003	7.7	8.0	6.5	-4.2	-7.4	-7.6	-6.9	-10.7
		1997	48.0	54.7	26.0	-9.1	-9.4	-10.1	-12.4	-28.1
		1993	81.2	86.8	65.3	-4.9	-8.5	-8.1	-6.3	-31.5
		1988	174.7	190.3	77.9	3.7	-4.6	-1.9	-7.1	-34.6
P. glehnii	18	2013	-1.8	0.0	0.0	-0.9	-1.8	0.0	0.0	-0.9
		2010	6.0	6.9	10.3	-0.2	6.0	6.9	10.3	-0.2
		2006	2.8	3.0	3.3	1.9	2.8	3.0	3.3	1.9
		2003	10.3	8.9	3.8	-28.1	-1.0	-1.0	-2.8	-31.0
		1997	7.8	9.4	-11.9	-28.3	-16.2	-12.6	-23.7	-37.8
		1993	7.7	10.9	-6.4	-25.6	-28.6	-22.4	-25.6	-40.0
		1988	23.6	30.2	-1.9	-29.6	-39.2	-28.0	-31.9	-50.6
P. glehnii	19	2013	0.0	0.0	0.0	-2.8	0.0	0.0	0.0	-2.8
		2010	-0.3	-3.6	-3.8	-3.8	-0.3	-3.6	-3.8	-3.8

	With stumps (*R-O*)/*O*				**Without stumps (*R-O*)/*O***			
2006	-10.0	-12.0	-12.8	-5.2	-10.0	-12.0	-12.8	-5.2
2003	-1.9	-6.3	-10.7	-21.7	-23.4	-25.1	-25.1	-27.7
1997	-7.1	-8.6	-15.0	-15.6	-45.8	-44.9	-43.7	-38.0
1993	-17.1	-15.7	-21.1	-12.5	-55.5	-52.9	-52.4	-40.1
1988	34.6	36.0	25.6	2.5	-56.0	-51.3	-51.3	-40.6

Table 4. 2 Decay classification of the stumps in the study plots with estimated and actual cutting dates. Absent stumps (i.e. stumps that could not be found at the time of field sampling) were also included. G = stump is gone and could not be sampled

Plot No.	Stump No.	Decay classes	Number of rings	Estimated cutting date	Actual cutting date
8	27	1	27	2000	2001
8	29	1	28	2001	2001
8	31	1	15	1988	1997
8	33	1	26	1999	2001
8	35	1	28	2001	2001
8	54	1	28	2001	2001
8	73	1	24	1997	2001
8	101	1	27	2000	1997
8	105	1	20	1993	2002
8	113	1	21	1994	2000
8	155	1	34	2007	2007
8	51	2	25	1998	2001
8	1	2	26	1999	2002
8	19	2	28	2001	2002
8	22	2	28	2001	2001
8	62	2	26	1999	2001
8	64	2	23	1996	2001
8	65	2	22	1995	1997
8	88	2	26	1999	2000
8	94	2	25	1998	1997
8	122	2	21	1994	1997
8	60	3	27	2000	2001
8	17	3	17	1990	2001
8	25	3	23	1996	2001
8	36	3	16	1989	1997
8	39	3	16	1989	2001
8	41	3	19	1992	2001
8	45	3	24	1997	2001
8	48	3	18	1991	2001
8	52	3	26	1999	2001
8	57	3	21	1994	1997
8	75	3	23	1996	2001
8	82	3	17	1990	1997
8	83	3	19	1992	1997
8	87	3	25	1998	2004
8	90	3	18	1991	2002
8	93	3	22	1995	1997
8	130	3	13	1986	1988
8	111	G	-	-	1988
8	68	G	-	-	2001
8	84	G	-	-	1997
8	104	G	-	-	1997
8	133	G	-	-	1997

Plot No.	Stump No.	Decay classes	Number of rings	Estimated cutting date	Actual cutting date
8	167	G	-	-	2000
8	69	G	-	-	1997
8	71	G	-	-	2001
8	110	G	-	-	1998
8	123	G	-	-	1997
9	68	1	17	1990	1997
9	70	1	27	2000	2001
9	72	1	26	1999	2001
9	20	2	24	1997	2001
9	17	2	20	1993	2000
9	29	2	24	1997	2001
9	31	2	24	1997	2001
9	36	2	27	2000	2001
9	41	2	17	1990	1997
9	45	2	22	1995	1997
9	54	2	23	1996	1997
9	57	2	14	1987	1997
9	61	2	24	1997	2001
9	67	2	23	1996	1997
9	74	2	28	2001	2001
9	79	2	16	1989	2000
9	171	2	21	1994	1997
9	103	2	7	1980	1997
9	111	2	24	1997	1997
9	33	3	19	1992	2001
9	42	3	26	1999	2001
9	51	3	14	1987	2001
9	63	3	22	1995	2001
9	76	3	23	1996	1997
9	1	3	14	1987	2000
9	22	3	26	1999	2001
9	26	3	26	1999	2001
9	39	3	14	1987	1997
9	44	3	18	1991	2001
9	46	3	28	2001	2001
9	48	3	9	1982	2001
9	56	3	10	1983	1997
9	59	3	14	1987	1997
9	95	3	13	1986	2000
9	131	3	17	1990	2002
9	134	3	17	1990	2008
9	139	3	16	1989	1997
9	149	3	19	1992	1997
9	150	3	21	1994	2000
9	152	3	30	2003	2008
9	155	3	14	1987	2000
9	24	G	-	-	1997
9	27	G	-	-	2001

Plot No.	Stump No.	Decay classes	Number of rings	Estimated cutting date	Actual cutting date
9	53	G	-	-	1993
9	65	G	-	-	1997
9	89	G	-	-	1997
9	91	G	-	-	1997
9	113	G	-	-	1997
9	124	G	-	-	1997
9	147	G	-	-	1997
9	179	G	-	-	1997
14	37	1	29	2002	2004
14	39	1	25	1998	2004
14	83	2	23	1996	2004
14	89	2	26	1999	2004
14	25	3	19	1992	2004
14	94	3	16	1989	2003
14	30	3	13	1986	2003
14	32	3	28	2001	2004
14	97	3	15	1988	2003
14	24	3	19	1992	2004
14	54	3	27	2000	2004
14	3	3	16	1989	2001
14	50	3	14	1987	2003
14	1	G	-	-	2001
14	2	G	-	-	2001
14	18	G	-	-	2001
14	22	G	-	-	2004
14	34	G	-	-	2004
14	58	G	-	-	2004
14	60	G	-	-	2004
14	65	G	-	-	2004
14	74	G	-	-	1994
14	78	G	-	-	1995
14	86	G	-	-	2003
14	91	G	-	-	2001
15	13	1	31	2004	2004
15	97	1	24	1997	2004
15	38	1	25	1998	2004
15	82	2	30	2003	2004
15	32	2	30	2003	2004
15	39	2	26	1999	2004
15	24	2	22	1995	2004
15	54	2	24	1997	2004
15	77	2	20	1993	2000
15	12	2	28	2001	2001
15	66	2	26	1999	2004
15	94	3	25	1998	2003
15	33	3	18	1991	2000
15	35	3	22	1995	2004
15	21	3	17	1990	2001

Plot No.	Stump No.	Decay classes	Number of rings	Estimated cutting date	Actual cutting date
15	7	3	24	1997	2004
15	59	3	19	1992	2000
15	37	3	16	1989	2000
15	26	3	15	1988	2001
15	72	3	15	1988	2003
15	45	3	13	1986	2000
15	67	3	22	1995	2003
15	88	3	18	1991	2004
15	85	3	20	1993	2000
15	3	G	-	-	1997
15	4	G	-	-	2000
15	19	G	-	-	2004
15	42	G	-	-	1997
15	52	G	-	-	2000
15	53	G	-	-	2000
15	57	G	-	-	1997
15	83	G	-	-	1994
18	77	1	29	2002	2004
18	92	1	30	2003	2004
18	12	2	30	2003	2004
18	16	2	29	2002	2004
18	89	2	21	1994	1995
18	22	2	28	2001	2004
18	46	2	26	1999	2004
18	85	2	25	1998	2004
18	38	3	20	1993	2004
18	18	3	18	1991	2004
18	11	3	20	1993	2004
18	54	3	17	1990	2004
18	57	3	15	1988	2004
18	3	3	11	1984	2005
18	13	3	16	1989	2004
18	74	3	13	1986	2004
18	51	3	11	1984	2003
18	88	3	16	1989	2004
18	52	3	11	1984	2004
18	62	3	11	1984	2003
18	40	3	9	1982	2004
18	26	3	21	1994	2004
18	68	3	10	1983	2004
18	15	G	-	-	2000
18	24	G	-	-	2004
18	29	G	-	-	2004
18	33	G	-	-	2000
18	36	G	-	-	1995
18	48	G	-	-	1991
18	59	G	-	-	2000
18	81	G	-	-	2004

Plot No.	Stump No.	Decay classes	Number of rings	Estimated cutting date	Actual cutting date
18	94	G	-	-	2003
19	33	1	30	2003	2004
19	52	1	27	2000	2004
19	23	2	19	1992	2003
19	31	2	22	1995	2004
19	71	2	29	2002	2004
19	92	2	30	2003	2004
19	25	3	24	1997	2004
19	6	3	30	2003	2004
19	78	3	28	2001	2004
19	55	3	28	2001	2004
19	29	3	27	2000	2004
19	86	3	28	2001	2004
19	43	3	25	1998	2004
19	93	3	24	1997	2004
19	98	3	25	1998	2004
19	34	3	19	1992	2004
19	89	3	18	1991	2001
19	58	3	18	1991	2003
19	35	3	21	1994	2003
19	38	3	19	1992	2004
19	18	3	15	1988	2004
19	99	3	15	1988	2003
19	62	3	14	1987	2004
19	76	3	15	1988	2002
19	17	3	15	1988	2001
19	13	3	13	1986	2003
19	73	3	20	1993	2001
19	37	3	11	1984	2003
19	69	3	6	1979	2001
19	1	G	-	-	2004
19	3	G	-	-	2004
19	11	G	-	-	2004
19	54	G	-	-	2000

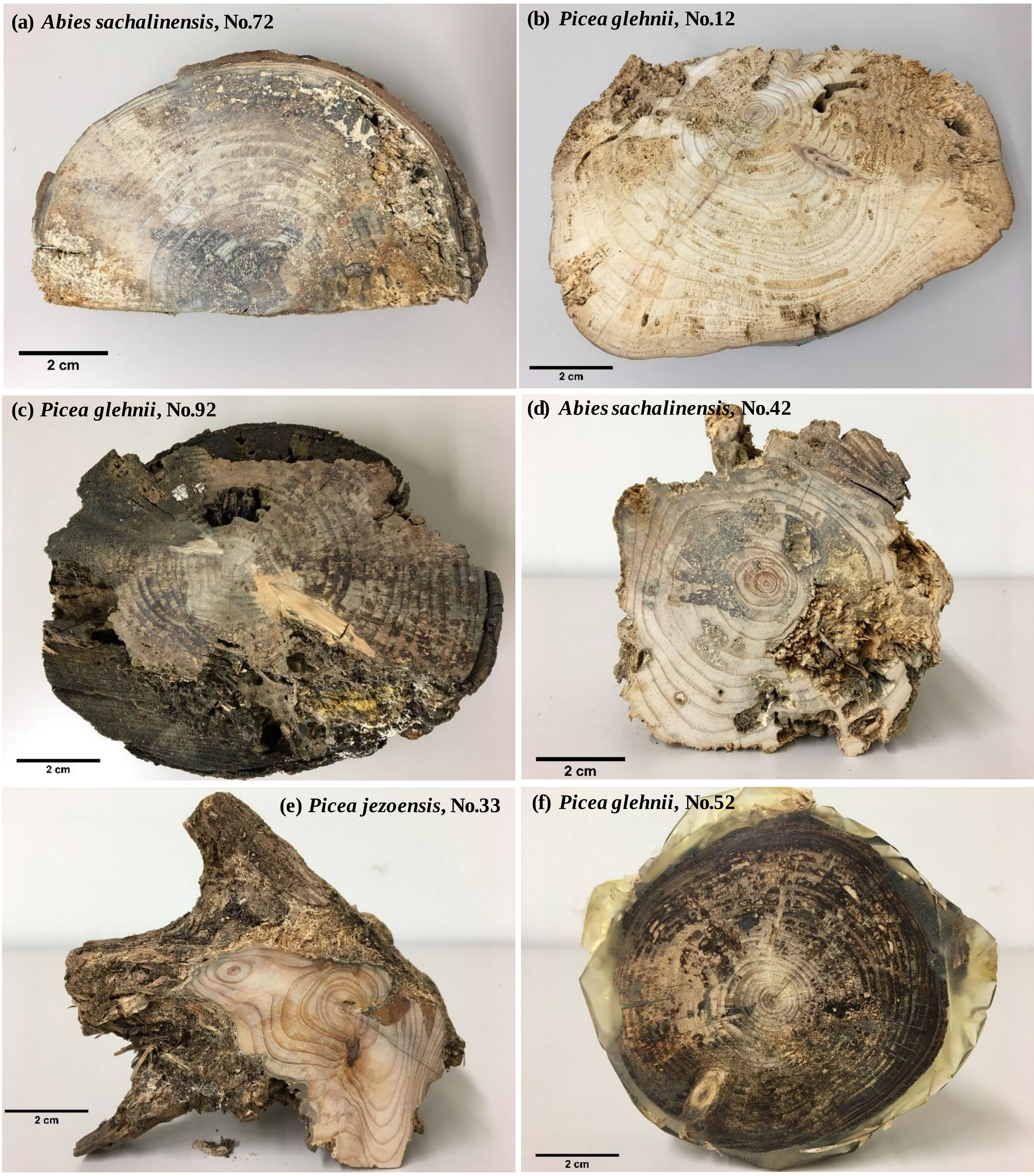

Fig. 4. 1 Examples of stump samples for (a) undecayed stump with intact bark; (b) undecayed stump with bark-less condition; (c) decaying stump with intact bark (at least at a small portion); (d) decaying stump with bark-less condition; (e) stump with poor circuit uniformity; (f) a sanded stump after applying epoxy resin. A scale bar in each photograph represents a length of 2 cm

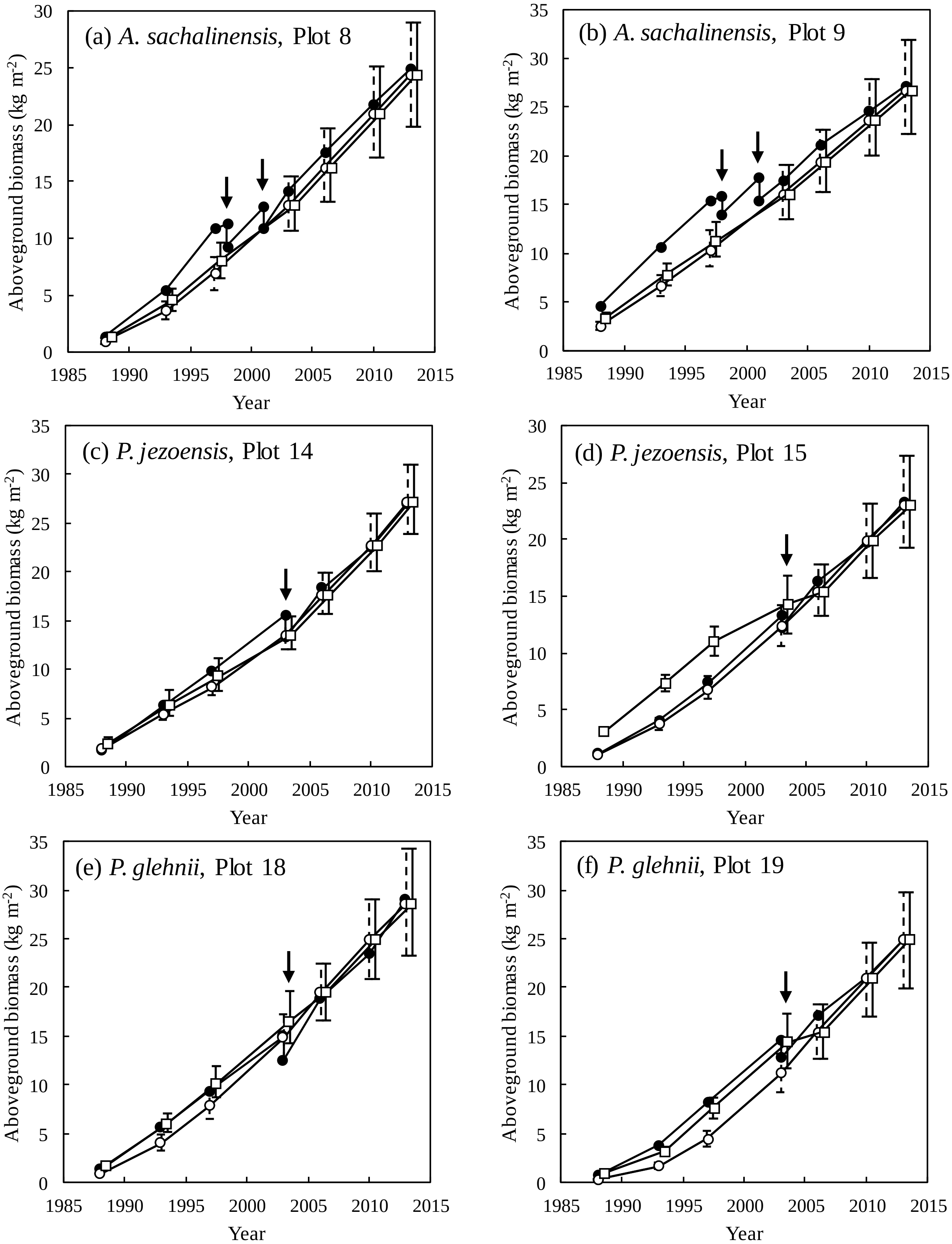

Fig. 4. 2 Relationships between reconstructed and observed values of aboveground biomass. ○, □, and ●, represent reconstructed values using original stand reconstruction, reconstructed values after adding the stumps and observed values, respectively. Arrows indicate main years of thinning operations. Solid and broken vertical bars indicate the upper and lower 95% confidence limits of the reconstructed values with and without stumps, respectively, based on the bootstrap method. The 95% confidence limits cannot be estimated for plot 18 in 1988

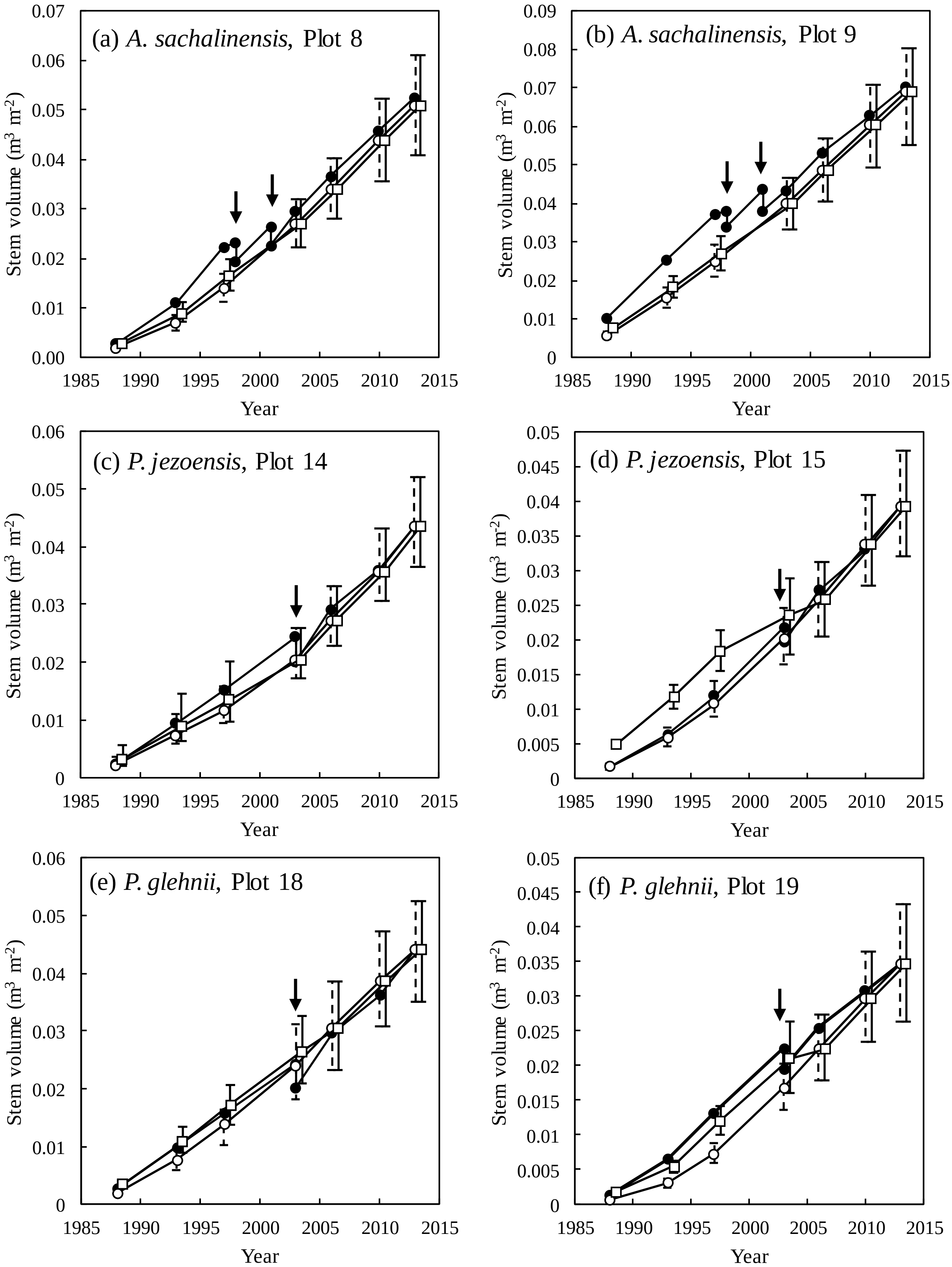

Fig. 4. 3 Relationships between reconstructed and observed values of total stem volume. ○, □, and ●, represent reconstructed values using original stand reconstruction, reconstructed values after adding the stumps and observed values, respectively. Arrows indicate main years of thinning operations. Solid and broken vertical bars indicate the upper and lower 95% confidence limits of the reconstructed values with and without stumps, respectively, based on the bootstrap method. The 95% confidence limits cannot be estimated for plot 18 in 1988

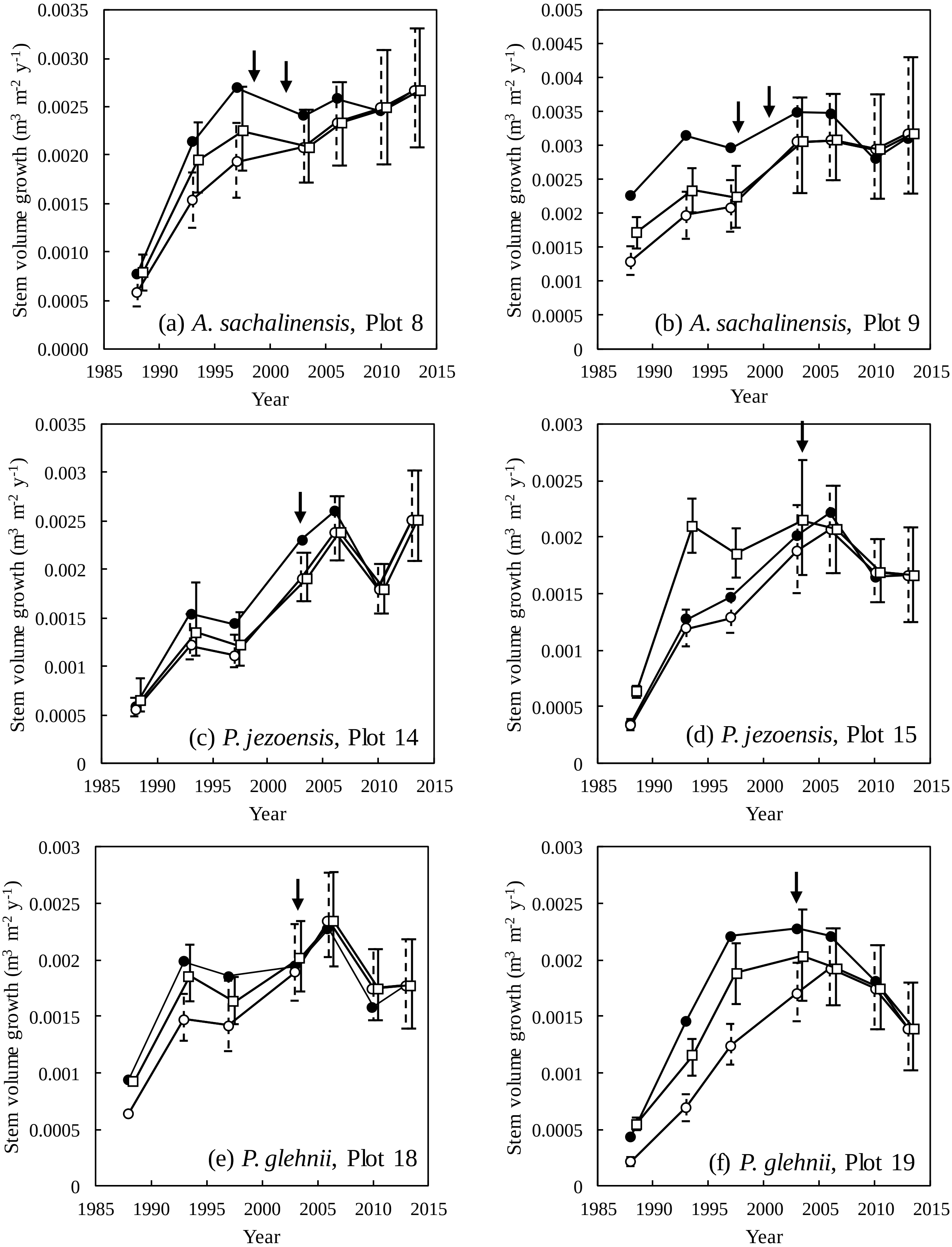

Fig. 4. 4 Relationships between reconstructed and observed values of stem volume growth. ○, □, and ●, represent reconstructed values using original stand reconstruction, reconstructed values after adding the stumps and observed values, respectively. Arrows indicate main years of thinning operations. Solid and broken vertical bars indicate the upper and lower 95% confidence limits of the reconstructed values with and without stumps, respectively, based on the bootstrap method. The 95% confidence limits cannot be estimated for plot 18 in 1988

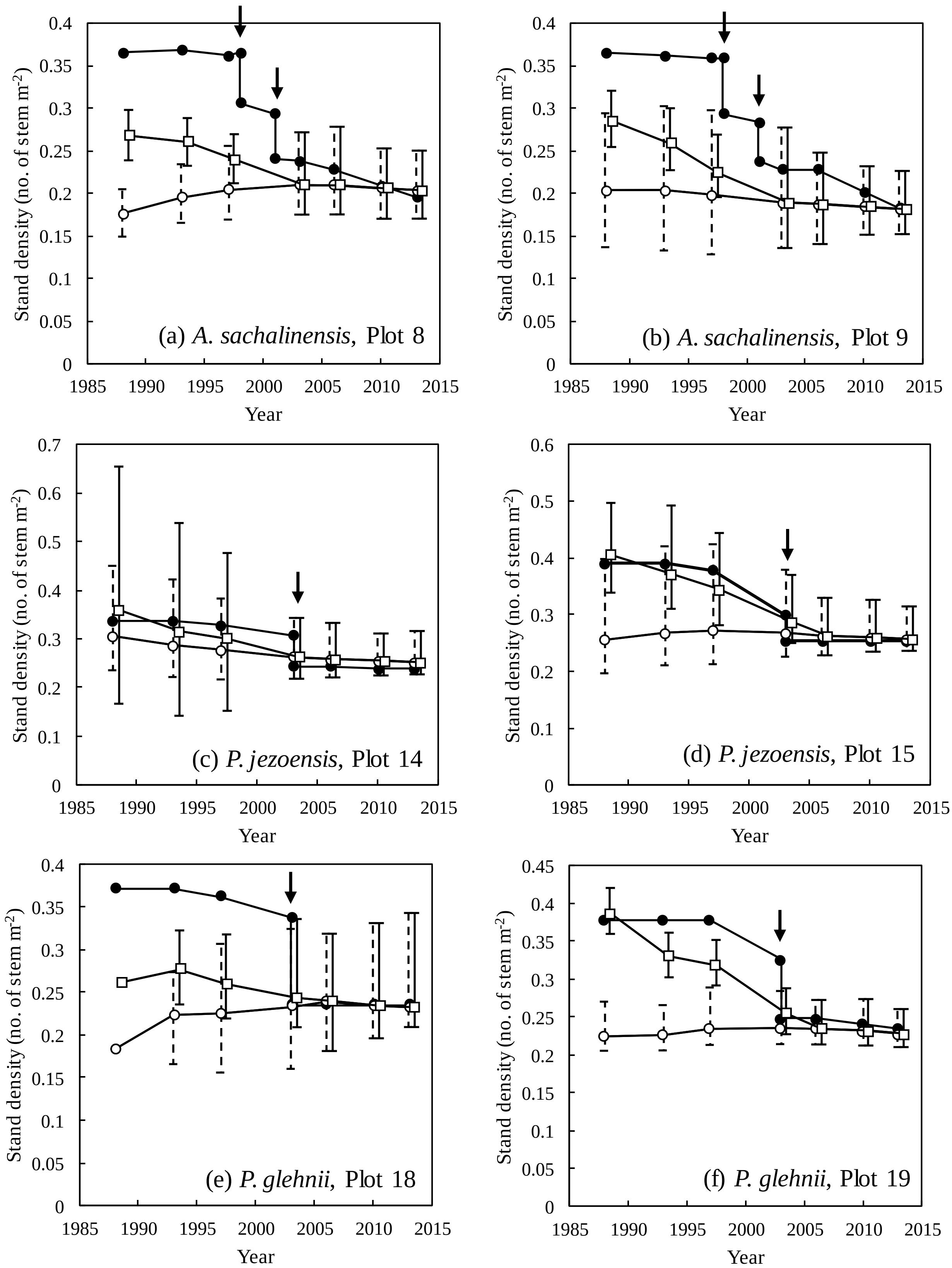

Fig. 4. 5 Relationships between reconstructed and observed values of stand density. ○, □, and ●, represent reconstructed values using original stand reconstruction, reconstructed values after adding the stumps and observed values, respectively. Arrows indicate main years of thinning operations. Solid and broken vertical bars indicate the upper and lower 95% confidence limits of the reconstructed values with and without stumps, respectively, based on the bootstrap method. The 95% confidence limits cannot be estimated for plot 18 in 1988

CHAPTER 5
General Discussion and Conclusion

In this thesis, I examined and explained the thinning effects on the estimated stand variables for even-aged plantations by the stand reconstruction technique. Furthermore, I tested the potential improvement in the underestimated stand variables of the stand reconstruction technique by recruiting stump information into the analysis.

In Chapter 2, I discussed the effects of thinnings on the estimated stand variables by a stand reconstruction technique in the case of Sugi and Hinoki plantations. Sugi stands implemented two times of thinnings in 1980 and 1998, and thinning ratio by the 1998 event was 33%, 30% and 13% for plots A, B and C, respectively. Hinoki stand received three times of thinnings in 1973, 1977 and 2003. Percentage error of the estimates generally reported underestimated stand variables for years before the thinnings, in comparison to the observed values in both Sugi and Hinoki stands. Bootstrap method was used to estimate the 95% confidence intervals (C.I.) of the estimated means of the reconstructed stand variables. Results from bootstrap method generally showed lack of overlap and non-overlap patterns between the estimated 95% C.I of the mean of the reconstructed value and observed value before the thinning operations in both Sugi and Hinoki stands. This suggested that thinnings caused underestimation of estimated stand variables for years before the thinning operations.

In Chapter 3, I further explored the thinning effects on the estimates of stand variables by the stand reconstruction technique in the case of Sprue and Fir plantations with a level of thinning of only 15-20%, which is less than the case of Hinoki and Sugi plantations. Results from the percentage error indicated that accuracy of predictions in the stand reconstruction technique was affected by the thinnings, especially for the years before the thinning operations. Overall, the percentage error and estimates of the 95% C.I. by the bootstrap method generally suggested that moderate and large errors of underestimated stand variables appeared in the years before the thinning operations in all stand variables. In conclusion, I reiterated that the thinning effects caused underestimated stand variables in the stand reconstruction technique and these effects could be related to the degree of the thinnings (number of thinned trees), and tend to be more apparent particularly in stand density.

In Chapter 4, I examined the possibility of correcting the underestimated stand statistics for even-aged plantations of Spruce and Fir species by including stump information such as stump diameter and tree-ring information into the predictions. Results of percentage error suggested that adding the stump information to the estimated stand variables improved the predictions only minimally, particularly for years before the thinnings. In addition, bootstrap method was used to estimate the 95% confidence intervals (C.I.) of the estimated means of the reconstructed values with and without adding the stump information. I found that improvement of the predictions in aboveground biomass and total stem volume after adding the stump information depends on the decay rates of the stumps. Stumps of *A. sachalinensis* and *P. glehnii*, which are planted in a cool region, tend to decay slower than the other coniferous tree species. This study reported that *P. glehnii* decayed slower than the other two species and for this reason, improvement of the predictions in this species is better than the others. For stem volume growth, improvement of the predictions after adding the stump information was indicated in only three plots (among the six plots). For stand density, adding the stump information only slightly improved the predictions. The errors in the estimates of stand density loomed large for years before the thinning operations. Overall, the estimates of stand density did not reproduce the observed values well in most plots, indicating that reconstruction of stand density is generally more difficult than the other stand variables.

Including stump information in the predictions of stand variables by the current form of stand reconstruction technique is recommended. Although improvement in the predictions is minimal, this is probably due to the fact that Fir and Spruce plantations only received light thinnings at only 15-22% thinning ratio by tree numbers. The improvement could probably be explained more clearly if heavy thinning operation is implemented. Furthermore, the improvement in the predictions also depends on the stump species and stump quality. Tree stump species with slower decay rate, after recruiting into the stand reconstruction technique, showed significant improvement in the predictions. In addition, good stump qualities such as intact bark, and clear and firm tree rings are important factors that helps improve the predictions of the stand variables. The present study suggests that it is worthwhile to include dead stems created by various disturbances into the stand reconstruction calculations.

An alternative method to quantitatively reconstructing the structural changes in forest stands may be the use of permanent plots (e.g. Peet 1981). However, permanent plots are not ubiquitous and require longer periods of time to obtain necessary data to be able to quantitatively reconstruct the changes in forest stands. Abstract simulation modeling is another alternative (e.g. Kurz et al. 2008, 2009; Shugart 1984); however, it may be quantitatively much less representative of reality and harder to validate the predictions than the long-term observations. At this point, the stand reconstruction method appears to be another alternative and practical to study and observe long-term changes in forest development. The advantage of this method is its ability to estimate various quantities of the stand in the past, even if there were no records of the stand in the past. The disadvantage of this method is that its applicability so far limits to only single-species plantations and natural monocultures (but see Fujii, MS thesis (2016), for its possible application to mix-species stands). Prevalence of even-aged stands in boreal forests and temperate regions make the stand reconstruction technique useful. The next challenge is to further develop and extend the method to mixed-species or mixed-aged forests.

The improvement in predictions of the forest stand variables of the stand reconstruction technique by including stump information would allow us to analyze and observe forest biomass changes over time, and consequently, to understand changes in forest growth patterns.

Forest growth provides an important climate change feedback, as it affects carbon sequestration in the wood and therefore can alter carbon cycle and storage. As global temperature keeps rising, forest growth and productivity are very likely to be affected by warmer temperature. Studies in boreal forests, which is one of the most important forest carbon sinks, reveal that warmer temperature in recent decades has limited the growth of forests (e.g. Andrea and Andrew 2007). This result was totally contradicted to the common notion that increases in forest growth and productivity are correlated to warmer temperature in high-latitude regions. The divergence of forest growth and temperature resulted from direct temperature rise, and drought stress caused by higher evaporative demands in warmer temperature. Overall, the stand reconstruction method allows us to observe and understand forest growth patterns in the past, and its connections to climatic factors like temperature or precipitation. Such studies would largely contribute to the sustainable management of forests in the context of global climate change. And the stand reconstruction technique is likely to provide us a useful vehicle to further such studies. In fact, there has been development in the examination of changes in growth patterns in forest aboveground biomass in relation to climate variabilities based on the reconstructed values with the present technique (Kamara, personal communication). This analysis has suggested a possibility of simultaneous growth change events occurring at boreal forests at widely distant locations. Such an analysis has never been possible with the conventional methods of studying stand development ─ showing usefulness and potential of the structural stand reconstruction technique.

Future work to be continued from this study should focus on the effects of thinning method on the predicted forest stand variables. In other words, thinning effects on the prediction of diameter distribution is important and should be examined fully in the future research. In addition, future study should examine the effects of including stump information in heavily thinned even-aged plantations to see how information from dead stumps could improve the prediction in the stand reconstruction technique. Furthermore, comparing the effects of decay rates of stumps from different tree species in improving the forest stand variables of the stand reconstruction technique is another point to consider.

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