The Growth Response of Planted Red Pine (*Pinus Resinosa*) to Alternative Thinning Regimes

Jolanta Agnieszka Leń
Supervisors: Eric Agestam, Swedish University of Agricultural Sciences
Robert E. Froese, Michigan Technological University

Swedish University of Agricultural Sciences
Master Thesis no. 202
Southern Swedish Forest Research Centre
Alnarp 2012

Bilateral Cooperation

SLU

The Growth Response of Planted Red Pine (*Pinus Resinosa*) to Alternative Thinning Regimes

Jolanta Agnieszka Leń

Supervisors: Eric Agestam, Swedish University of Agricultural Sciences
Robert E. Froese, Michigan Technological University

Examiner: Urban Nilsson

Swedish University of Agricultural Sciences
Master Thesis no. 202
Southern Swedish Forest Research Centre
Alnarp 2012

MSc Thesis in Forest Management – Euroforester Master Program,
30 ECTS, Advanced level (A2E), SLU course code EX0630

Jolanta Leń has studied at SLU (Swedish University of Agriculture Sciences), Alnarp, Sweden and MTU (Michigan Technological University), Houghton, Michigan, USA.

This thesis represents a cooperative effort between SLU and MTU within the Atlantis program. The Atlantis programme in-turn results from a co-operation between the European Union and USA. It receives financial support from the European Commission, via the Education, Audiovisual land Culture Executive Agency (EACEA) and from the US Department of Education, via the Fund for the Improvement of Post Secondary Education (FIPSE).

Acknowledgements

I am grateful to the ATLANTIS program for the opportunity to study in the Transatlantic Master’s Degree Program in Forest Resources.

I would like to sincerely thank Gary Wykoff from Plum Creek Timber Company for sharing the data with me and the opportunity to work on this very interesting project.

Most of all I would like to thank my advisors, Eric Agestam and Robert Froese, for their invaluable help with the project.

Tremendous thanks to my family and friends, and especially to Michał Ferdyn, for being so supportive during the entire time I was studying abroad.

Abstract

Red pine (*Pinus resinosa* Ait.) plantations have been established in Michigan with expectations of mixed final product goals: pulpwood, boltwood and possibly sawlogs. The effects of alternative treatments on tree and stand attributes were examined in: the Atlantic Mine trial, thinned in spring 2006 with three alternatives: (1) every fifth row removal plus crown thinning, (2) every third row removal plus crown thinning and (3) every third row removal plus thinning from below; the Crane Lake trial, thinned in fall 2004 with two alternatives: (1) every third row removal and (2) every third row removal plus thinning from above; the Middle Branch East trial, thinned in fall 2004 with two alternatives: (1) every third row removal plus one in three remaining trees and (2) every third row removal plus one in five remaining trees. All trials included control plots where no thinning was applied. The trials were established in the field as a randomized complete block experiments, in which individual trees were measured in 3-4 fixed-area plots located within each treatment unit. Growth responses of diameter at breast height, height, live crown length, stand basal area and stand volume were examined along with their increments. The Tukey multiple comparison test was used to detect significant differences between treatments in their effect on tree growth response. The results showed that diameter increment increased with increasing thinning intensity and was significantly larger in thinned plots compared to unthinned. Treatments did not substantially affect average tree height increment. Stand basal area increment was significantly larger in the control plot only the year after the harvest. Volume increment was significantly larger in controls, but did not differ considerably among remaining treatments. However, the ratio of volume increment to standing volume was significantly smaller in unthinned plots compared to thinned. Since thinning treatments in all trials hardly ever differed significantly in their effect on stand growth response, mainly due to the relatively short time of the evaluation, heavier thinnings should be favored due to higher volume increment rates and shorter time needed to reach desirable diameters. Nevertheless, economic evaluation based on obtained results will be conducted in the future in order to make final decisions about the most profitable treatment.

Key words: red pine, thinning, growth response, volume, diameter at breast height

Table of contents

1. Introduction

1.1 Red pine in the Great Lakes Region

Red pine (*Pinus resinosa* Ait.) is one of the major coniferous tree species in the Great Lakes region of the United States (the states of Michigan, Minnesota and Wisconsin). The species occurs naturally in monocultures as well as in mixed stands with white pine (*Pinus strobus* L.), jack pine (*Pinus banksiana* Lamb.), aspen (*Populus sp.)*, paper birch (*Betula papyrifera* Marsh.) and oaks (*Quercus* sp.), generally on dry sandy soils of low fertility (Farrar 1995; Ek et al. 2006).

Red pine is a species well adapted to frequent low intensity fires; therefore, before large-scale logging in the 19^{th} century, this disturbance enhanced the natural regeneration in multi-cohort structures (Atwell et al. 2008; Drobyshev et al. 2008a). At the present time the species occurs mostly in even-aged stands of simple structure because of planting (Palik and Zasada 2003).

At the time of European settlement combined red pine and white pine forest types covered an estimated 8.9 million hectares (of which one-third was red pine). However, this area decreased significantly over time due to extensive logging, conversion to agriculture and fire suppression policy (Buckman et al. 2006; Gilmore and Palik 2006; Drobyshev et.al. 2008b). Planting programs by the Civilian Conservation Corps (in the 1930s) and the Michigan Department of Conservation (in the 1950s and 1960s) notably contributed to the fivefold increase in abundance of red pine in forests of the region, resulting in current coverage of approximately 769,000 hectares (Ek et al. 2006; Pilon 2006).

Red pine timber is highly utilized in the region and, thanks to modern technologies, managed for pulpwood, utility poles and dimension lumber (Martin and Lorimer 1996). Though, the species is planted not only for wood as a final product, but also as a wind- and snow-break and means to reduce movement of sand from dunes (Burns and Honkala 1990).

1.2 Thinning in red pine stands

Thinning is a silvicultural treatment performed to improve the quality of a stand by removal of unwanted trees and promoting growth of the residual trees. It improves growing abilities of the remaining trees due to improvement of light conditions and thermal conditions of the soil as well as through reduction of competition between remaining trees (Assmann 1970).

Thinning types most commonly used in red pine stands are:

- row (mechanical) thinning- removal of entire rows of trees;
- thinning from above (crown thinning)- removal of some trees from dominant or codominant (Oliver and Larson 1996) crown classes to enhance growth of trees in those same groups;
- thinning from below- removal of suppressed, intermediate (Oliver and Larson 1996) or smaller codominant trees;
- selection (dominant) thinning- removal of dominant trees to improve the growth of trees in lower crown classes (Helms 1998; Bradford and Palik 2009).

According to “A revised managers handbook for red pine in the North Central Region” (Gilmore and Palik 2006) there are no strict rules regarding thinning treatment in red pine stands. However, during each thinning not more than 50% of basal area should be removed. Moreover, in stands with an average diameter between 12 and 23 cm, stocking level of about 32 m^2ha^{-1} should be a determinant of readiness for thinning. Stocking charts (e.g. Benzie 1977) are useful tools for carrying out suitable thinning treatments in red pine plantations. They help managers to prevent not only high natural mortality in overstocked stands, but also damage related to understocking; for example susceptibility to wind falls (Youngblood 2011). Flexibility concerning choice of the type, timing and intensity of thinning guarantees reaching different management goals adjusted to particular site conditions.

1.3 The effect of a thinning

The result of a thinning depends on stand structure (tree species, age, basal area, density of stocking, site index) as well as on thinning characteristics: i.e. type, interval, grade, intensity and time of first thinning (Assmann 1970; Helms 1998).

One of the main effects and goals of a thinning is reduction of natural mortality by decreasing competition for resources (Powers et al. 2010). According to Assmann (1970), thinning leads to acceleration of tree growth, especially in the case of more heavily thinned young stands, which have not yet achieved their maximum current volume increment. However, this growth starts declining earlier than in stands that are more lightly thinned and at an older age, therefore eventually both stands may achieve similar mean annual volume increments. Extension of growing space due to thinning induces an increase in growth rate of live crown, which means enlargement of photosynthetic area (Assmann 1970). The other effect is higher diameter increment of trees remaining after thinning compared to trees in unthinned stands. Decline in mean length of logs cut from harvested trees is another result. There is no significant effect of a thinning on height of trees planted with reasonable spacing. Due to lower competition between trees they can invest resources in diameter increment. As a result larger diameters achieved in a shorter amount of time contribute to reduction of rotation length of a stand (Assmann 1970). Even though light and moderate treatment may increase gross stem volume production, generally thinning leads to its decrease (Nilsson et al. 2010). Thinning also has an impact on tree health. Lower competition between trees improves their vigor, which increases self-defense from pests and diseases (Ek et al. 2006).

To sum up, thinning is a proper tool for reduction of tree mortality, increasing growth of remaining trees as well as for affecting wood quality: external (tree dimensions, stem straightness and knots absence) and internal (width of annual rings, strength, etc.) which significantly change the economic value of a forest (Assmann 1970).

1.4 Former studies about thinning treatments in red pine stands

Several experiments have been conducted about thinning treatments in red pine stands. Growth and yield responses of red pine plantations to seven different thinning treatments were analyzed by Liechty et al. (1985). The results showed that diameter increment increased with decreasing stand density. Basal area increment did not differ among thinning intensities, but was significantly lower in the control plot. There was no significant difference in volume growth between all examined plots.

A long-term silvicultural experiment was examined by Bradford and Palik (2009). Stands were thinned 3 times at 5-10 year intervals to residual densities: 7, 14, 21, 28 and 34 m^2ha^{-1}. The results showed that dominant thinning resulted in smaller diameters, but significantly larger biomass and basal area growth compared to thinning from below. Importantly, these attributes were affected not only by thinning intensity, but also by stand age and residual basal area as well as by interaction between these characteristics.

Bradford et al. (2010) examined the influence of red pine stand age, thinning types and density expressed as residual basal area on growth dominance (relation between biomass and growth of individual trees as a share of all trees). Growth dominant trees are those for which increment as a proportion of stand increment exceeds the proportion of its biomass in stand biomass. The results of this research showed that growth dominance was positive and increasing in time in controls, negative in sparse and positive in dense stands thinned form above, and close to zero in stands were thinning from below or both, thinning from below and from above, were applied.

In their study D'Amato et al. (2010) focused on thinning effects on the development of red pine stands as well as on growth trends of thinned stands with extended rotation. They found out for example that after 52 years of repeated thinnings quadratic mean diameter was the largest in stands thinned to lowest densities (13.8 m^2ha^{-1}), but not significantly different among others (18.4, 23, 27.5 and 32.1 m^2ha^{-1}). However, cumulative volume production for this treatment was significantly lower compared to remaining thinnings, which did not differ significantly from each other.

The effects of different thinning treatments (types and intensities) on trends in mortality in red pine stands were studied by Powers et al. (2010). The results of this study showed that thinning type, along with stocking density, had a substantial effect on tree mortality. Thinning from below reduced mortality on higher grade compared to thinning from above, which resulted in retention of smaller trees which are usually less vigorous than removed larger individuals.

Powers et al. (2011) examined the impact of different silvicultural approaches (including thinning grades to residual basal area of 14, 18, 23, 28 and 32 m^2ha^{-1}) on carbon storage in red pine stands. Their results showed that total carbon storage was larger in unthinned stands, but still alike for all treatments. Carbon storage of trees in overstory was higher in unthinned stands, and among thinned stands it was larger for the lowest intensity thinning. There was no difference between treatments in the case of understory carbon storage, while its amount in deadwood was 6-13 times higher in controls compared to thinned plots.

What is also important is that several guides for red pine stands management are available, e.g.: “Red Pine Management Guide” by Ek et al. (2006) or “A Revised Managers Handbook for Red Pine in the North Central Region” by Gilmore and Palik (2006). Even so, there is a need for detailed information about stand response to proposed thinning treatments in particular stand conditions, which would help manage red pine plantations even more profitably.

2. The objective of the study

Plum Creek owns and manages approximately 2.75 million ha of timberland in 19 states (Plum Creek Timber Company 2011). Red pine plantations cover 48,600 ha in two Lake States, Michigan and Wisconsin, and 9,900 ha in Maine (Wykoff 2011). The red pine thinning trials analyzed in the following thesis have been established to assess operational methods that may maximize financial returns and provide for the highest value products under past high density planting regimes. The aim of the study is to compare the effects of different thinning treatments on the growth responses of diameter at breast height, total tree height, live crown length, crown ratio, stand basal area and stand volume. I hypothesize that thinning has more favorable effect on growth of remaining trees than “no thinning” in red pine stands. Moreover, relations between particular characteristics: diameter and height, diameter and live crown length, average live crown length and stand basal area, average height and stand volume, average live crown length and stand volume, average diameter and stand volume, stand basal area and stand volume, over the time for different treatments will be compared. The most effective thinning treatment in particular site conditions will be identified.

3. Methods

3.1 Study site

Data used in the following thesis come from three study plots established by Plum Creek Timber Company: the Atlantic Mine Thinning Trial, the Crane Lake Thinning Trial and the Middle Branch East Thinning Trial.

3.1.1 Study description

The thinning trials were established as a formal experiments using a randomized complete block design, with three (or four in the Crane Lake) blocks and three (or four in the Atlantic Mine) thinning treatments. Four (three in the Atlantic Mine) plots within each block- treatment combination were established before thinning; therefore the design also includes sub-sampling within each TU. Each subplot included 18 to 24 trees before the thinning. Treatments were slightly different at each site, but reflected the same overall objective of testing growth response to increasing intensity and complexity of thinning.

Measurements of diameter at breast height (DBH, diameter)) [cm] were performed every year and measurements of total tree height (THT, height) [m] and live crown length [m] every other year (or in 2005, 2008 and 2010 in the case of the Atlantic Mine trial).

Based on collected data, following stand-level attributes were calculated for each treatment unit: cm^2

- Tree basal area, further summed for all trees and converted to mean BA per hectare:
  $\mathrm{BA}\ [\mathrm{m}^2] = 0.00007854 \cdot \mathrm{DBH}^2\ [\mathrm{cm}^2]$;
- quadratic mean diameter, which is preferred mensurational representation of average stand diameter (Curtis and Marshall 2000):
  $\mathrm{QMD}\ [\mathrm{cm}] = \sqrt{(\sum_{i=1}^{n} \mathrm{DBH}^2)/n}$, for trees: i =1 to n;
- tree volume, further summed for all trees and converted to mean volume per hectare:
  $\mathrm{v}\ [\mathrm{m}^3] = 0.00013026 \cdot \mathrm{DBH[in]}^{1.8598} \cdot \mathrm{THT[ft]}^{0.9299}$ (Gilmore 2005);
- ratio of volume increment (1- or 2-year) to standing volume, which is the attribute preferred to volume increment due to different initial values of volume and short time of observation:

$$\text{volume ratio} = \frac{\text{volume}_{\text{year 2}} - \text{volume}_{\text{year 1}}}{\text{volume}_{\text{year 1}}};$$

– ratio of live crown length to tree height:

$$\text{crown ratio} = \frac{\text{live crown length}}{\text{tree height}}.$$

Additionally increments (delta) of most attributes, including: basal area, diameter at breast height, quadratic mean diameter, volume, height and live crown length, were calculated. Therefore for example "increment in 2008" in the following thesis means one-year increment (from 2007 to 2008) for diameter, quadratic mean diameter and basal area, and two-year increment for height, live crown length, height to live crown and volume. The exception is the Atlantic Mine site for which annual increments were calculated due to lack of uniformity in years of measurements.

Moreover, summaries of stand basal area, stand volume and number of trees per hectare before and after the harvest were prepared. All study plot sizes were recalculated after the thinning for adequate "per hectare representation" (more details are given further in this chapter). Therefore information about diameter at breast height, tree height and length of live crown is lacking, and it was not possible to prepare pre- and post- thinning comparisons of these attributes.

3.1.2 Study plots

The location of thinning trials analyzed in this thesis is presented in Fig. 3.1.

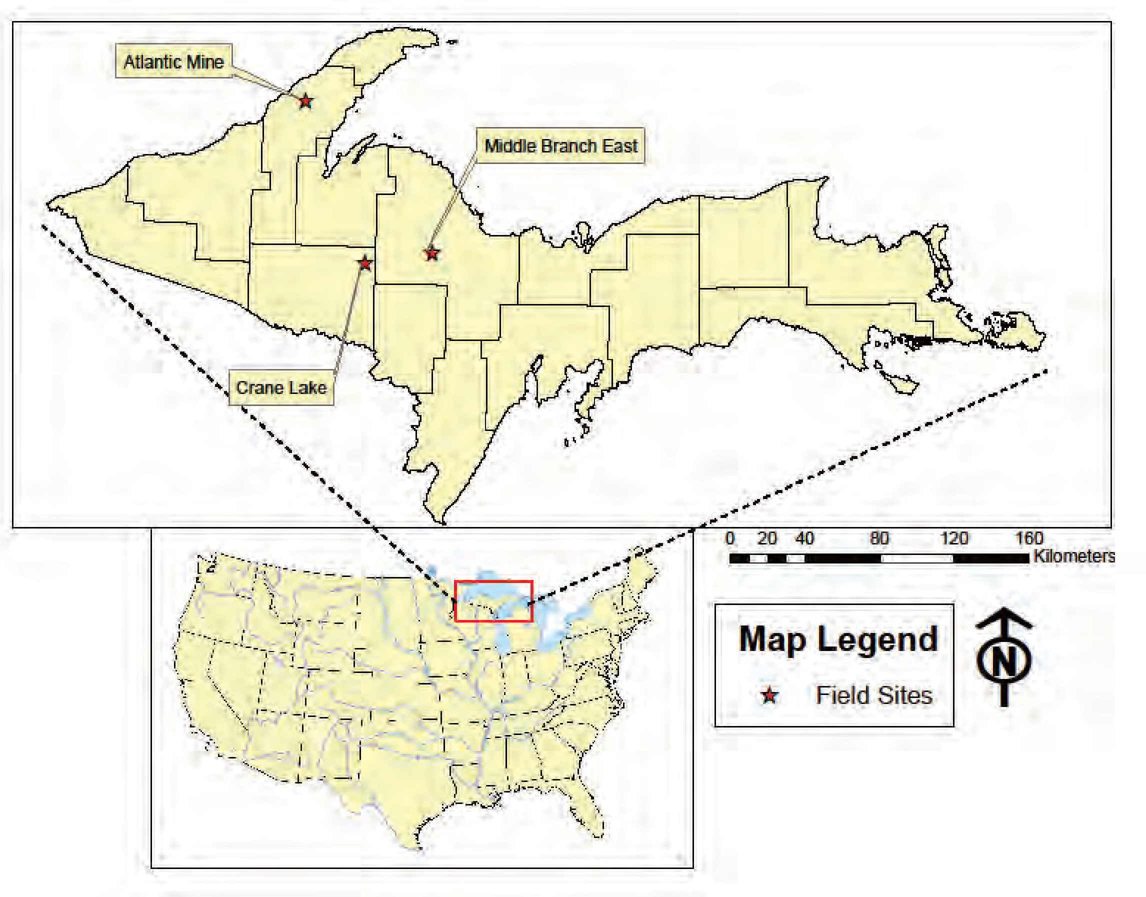

Fig. 3.1 Location of thinning trials in Michigan.

3.1.2.1 Atlantic Mine Thinning Trial

The stand was planted in May 1985 on a Site Index 25 m at the age of 50 years. Soil is Houghton 139-D: Trimountain- Paavola- Waiska complex with loamy sand surface texture. The site is coarse- textured till (Wykoff 2011). Initial number of trees was 1820 per hectare.

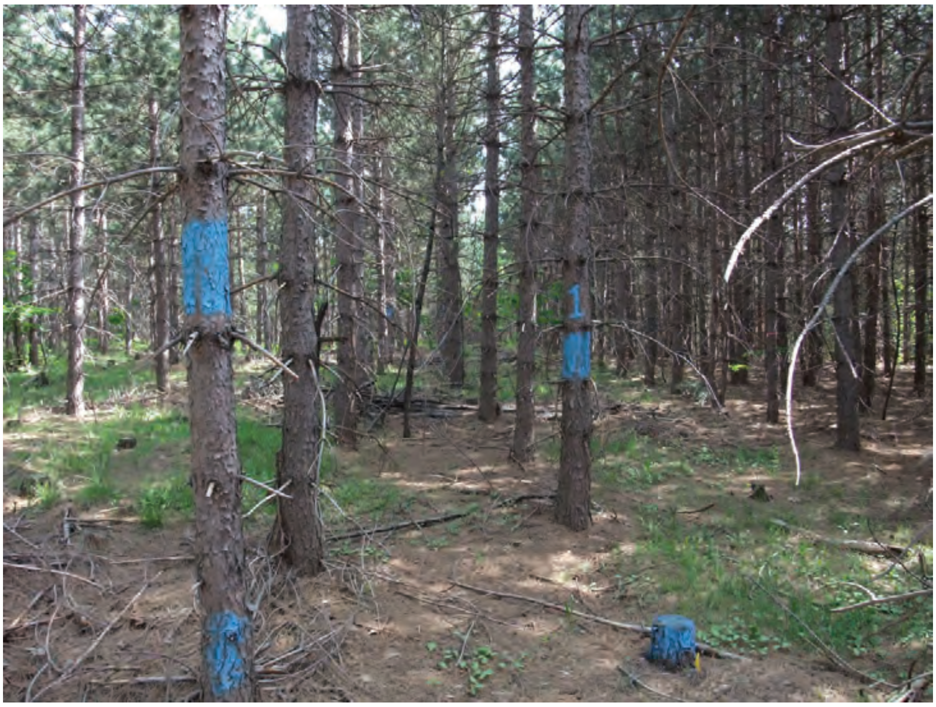

Fig. 3.2 Study subplot in the Atlantic Mine trial.

Four treatments in three blocks were applied in May 2006:

– **Treatment 1**: removal of one in five rows and crown thinning (i.e. one in five trees), residual BA= 25 m^2ha^{-1};
– **Treatment 2**: removal of one in three rows and crown thinning (i.e. one in five trees), residual BA= 21.5 m^2ha^{-1};
– **Treatment 3:** removal of one in three rows and thinning from below in two residual rows, residual BA= 24 m^2ha^{-1};
– **Treatment 4**: no thinning (control plot), BA= 43.3 m^2ha^{-1}.

Number of stems before and after the harvest is presented in Fig. 3.3.

Measurements for condition at the end of the growing season in 2005 were performed in May 2006 prior to the harvest. Three permanent rectangular plots within each treatment were established before the harvest. Every tree has been numbered. Detailed information about stand structure is summarized in the Table 3.1.

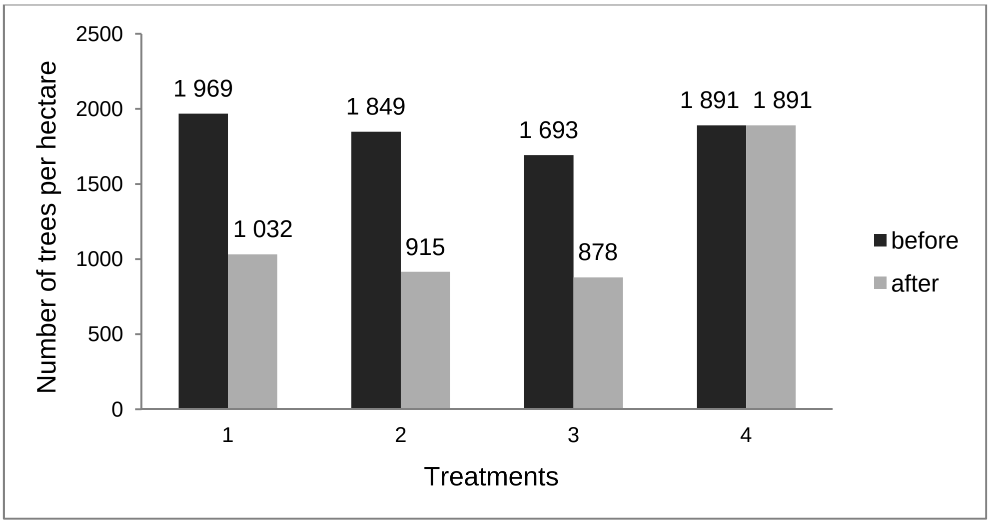

Fig. 3.3 Average number of trees per hectare in the Atlantic Mine before and after the harvest in 2005 for different thinning treatments: 1- removal of every fifth row plus crown thinning in residual rows, 2- removal of every third row plus crown thinning in residual rows, 3- removal of every third row plus thinning from below, 4- no thinning (control plot).

Table 3.1
Summary of pretreatment stand attributes in the Atlantic Mine Thinning Trial.

Block	DBH [cm]	Height [m]	Live crown length [m]	Basal area [m^2ha^{-1}]	Volume [m^3ha^{-1}]	Number of trees per ha
Treatment 1	**17.0**	**10.41**	**4.99**	**45.27**	**240.59**	**1969**
A	17.2	10.06	4.87	43.88	225.22	1867
B	17.3	10.72	5.27	45.66	246.70	1913
C	16.4	10.46	4.83	46.27	249.84	2127
Treatment 2	**16.8**	**10.31**	**5.02**	**41.46**	**219.32**	**1849**
A	16.7	9.72	4.93	40.01	200.85	1759
B	16.6	10.35	5.16	38.93	205.98	1784
C	17.0	10.87	4.97	45.44	251.12	2002
Treatment 3	**17.7**	**10.39**	**4.96**	**42.43**	**222.93**	**1693**
A	17.7	9.89	4.85	44.23	223.15	1745
B	17.5	10.59	4.96	40.44	215.54	1638
C	17.7	10.70	5.09	42.62	230.11	1695
Treatment 4	**16.9**	**10.26**	**5.02**	**43.32**	**227.15**	**1891**
A	16.9	9.92	5.16	39.97	202.42	1733
B	16.7	10.30	5.03	45.76	242.23	2025
C	17.0	10.72	4.78	44.66	241.61	1928

3.1.2.2 Crane Lake Thinning Trial

The stand was planted in October 1984 on a Site Index 27 m at the age of 50 years and habitat type ATD to AVO (Burger and Kotar 2003). Soil opportunity class is B, soil stability rating is 2 and soil map unit is Iron County 110B, Petticoat- Wabeno very stony silt loam. The site is a nearly level ground moraine with moderate available water capacity, moderately well drainage class and a seasonal high water table between 0.5 and 1.2 m (Wykoff 2011). Initial number of trees was 2200 per hectare.

Fig. 3.4 Study subplot in the Crane Lake trial.

Three treatments in four blocks were applied in August/ September 2004 with cut-to-length processor:

- **Treatment 1**: removal of every third row, residual BA= 28.5 m^2ha^{-1};
- **Treatment 2**: removal of every third row and crown thinning (i.e. one in five trees), residual BA= 22.7 m^2ha^{-1};
- **Treatment 3**: no thinning (control plot), BA=47.4 m^2ha^{-1}.

Number of stems before and after the harvest is presented in Fig. 3.5.

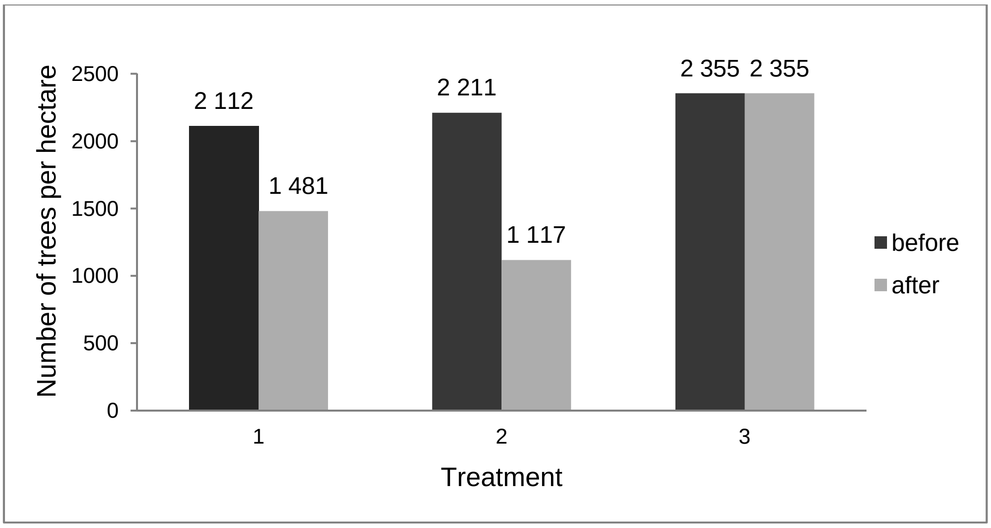

Fig. 3.5 Average number of trees in the Crane Lake before and after the harvest in 2004 for different thinning treatments: 1- removal of every third row, 2- removal of every third row and crown thinning, 3- no thinning (control plot).

Table 3.2
Summary of pretreatment stand attributes in the Crane Lake Thinning Trial.

Block	**DBH [cm]**	**Height [m]**	**Live crown length [m]**	**Basal area [m^2ha^{-1}]**	**Volume [m^3ha^{-1}]**	**Number of trees per ha**
Treatment 1	15.5	10.34	4.93	40.85	217.68	2112
A	15.5	10.22	4.76	40.91	214.60	2096
B	15.4	10.21	4.87	38.26	202.12	1975
C	15.2	10.34	4.99	42.79	229.38	2274
D	15.7	10.59	5.11	41.45	224.63	2104
Treatment 2	15.5	10.64	4.92	42.91	184.46	2211
A	15.5	10.73	4.68	45.37	186.55	2336
B	15.6	10.16	4.92	39.54	175.34	2012
C	15.2	11.07	5.01	43.53	194.98	2308
D	15.5	10.61	5.08	43.20	180.98	2190
Treatment 3	15.9	10.90	5.00	47.35	262.87	2355
A	16.8	11.01	4.96	45.25	252.21	1997
B	15.9	11.10	5.11	50.29	283.21	2503
C	15.8	10.84	4.91	47.60	265.36	2393
D	15.2	10.69	5.02	45.75	248.04	2439

Four permanent rectangular plots within each treatment were established before the harvest. Every tree has been numbered. Treatment length was 213 m, widths varied from 21 to 30 m across the treatments, and sizes of subplots varied from 77 m^2 to 193 m^2 after the thinning. Plot sizes after the harvest for the treatments 1 and 2 were extended to include the row which was removed. Description of stand structure is summarized in the Table 3.2

3.1.2.3 Middle Branch East Thinning Trial

The stand was planted in spring 1978 on the Site Index 20 m at the age of 50 years and habitat type AQVac. Soil opportunity class is C, soil stability rating is 1 and soil map unit is Sayner- Rubicon 80B, which means sand or sand- gravel substratum under strongly acidic sands. The site has very low available water capacity and is characterized by excessively drained drainage class and seasonal high water table greater than 1.8 m (Wykoff 2011). Initial number of trees was 1800 per hectare. Spacing between rows is about 2.5 m and about 1.5—2.5 m within rows.

Fig. 3.6 Study subplot in the Middle Branch East trial.

Three treatments in three blocks were applied in November 2004 with cut-to-length processor:

– **Treatment 1**: removal of every third row and crown thinning in remaining rows (i.e. one in three trees), residual BA= 17.6 m^2ha^{-1};

– **Treatment 2**: removal of every third row and crown thinning in remaining rows (i.e. one in five trees), residual BA= 20.5 m^2ha^{-1};

– **Treatment 3**: no thinning (control plot), BA= 39 m^2ha^{-1}.

Number of stems before and after the harvest is presented in Fig. 3.7.

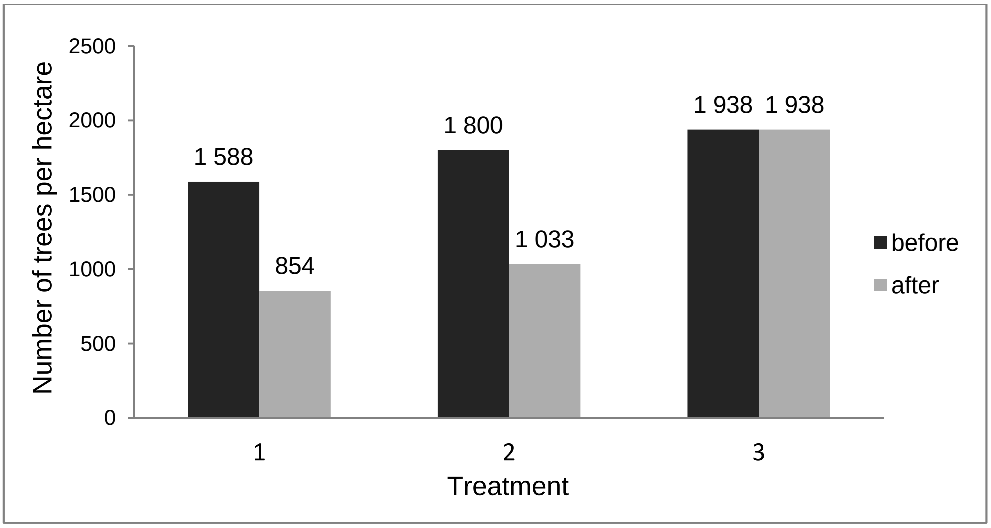

Fig. 3.7 Average number of trees per hectare in the Middle Branch East before and after the harvest in 2004 for different thinning treatments: 1- removal of every third row plus one in three dominant or codominant trees, 2- removal of every third row plus one in five dominant or codominant trees, 3- no thinning (control plot).

Four permanent rectangular plots (including at least 16 trees) within each treatment were established before the harvest. Every tree has been numbered. Trial dimensions were 240 by 201 m (N—S) and 180 by 196 m (E—W). Treatment lengths varied from 195 to 227 m, widths varied from 17 to 25 m across the treatments and sizes of subplots varied from 89 m^2 to 252 m^2 after the thinning. Plot sizes after the harvest for the treatments 1 and 2 were extended to include the row which was removed. Means of stand structure characteristics before the thinning are presented in the Table 3.3.

Table 3.3
Summary of pretreatment stands attributes in the Middle Branch East Thinning Trial.

Block	DBH [cm]	Height [m]	Live crown length [m]	Basal area [m^2ha^{-1}]	Volume [m^3ha^{-1}]	Number of trees per ha
Treatment 1	**15.6**	**10.61**	**6.39**	**31.43**	**173.62**	**1588**
A	16.0	10.26	6.50	27.75	147.87	1324
B	16.1	10.90	6.38	35.01	196.23	1647
C	14.6	10.68	6.30	31.52	176.75	1792
Treatment 2	**15.4**	**10.77**	**6.32**	**35.01**	**197.00**	**1800**
A	15.6	10.72	6.35	37.66	212.42	1879
B	15.3	10.69	6.22	31.07	172.49	1634
C	15.4	10.91	6.38	36.30	206.08	1886
Treatment 3	**15.6**	**11.07**	**6.18**	**38.95**	**224.32**	**1938**
A	15.1	10.94	5.94	39.62	227.76	2114
B	16.4	11.63	6.35	41.07	244.19	1862
C	15.4	10.64	6.24	36.17	201.01	1837

3.2 Data analysis

The data were prepared and analyzed in R (R Development Core Team 2011) and Microsoft Excel.

The analysis of variance was performed to identify significant differences between the effects of different thinning types on stand growth responses. Because of occurrence of multiple plots with multiple trees within each treatment, randomized complete block design (RCBD) with sub-sampling was applied ("*stand attribute*~ treatment+ block+ Error(plot)" code in R). Blocks, treatments and plots were treated as factors. The "Error" function was applied due to subsampling. According to Kutner et al. (2005) the analysis could be performed only for data with no relevant interaction between blocks and treatment. The following tools were used to check the assumptions of performed analysis:

– Shapiro test for normal distribution (Null hypothesis states normal distribution);
– Bartlett test for homogeneity of variances (Null hypothesis states no significant difference between variances among tested groups);
– two-way interaction plot for no interaction between blocks and treatments (interaction between factors indicated by nonparallelism of the lines (Zar 2010)).

The analysis of variance for quadratic mean diameter was dropped due to occurrence of variance heterogeneity.

Since the values of particular stand characteristics (basal area, diameter, height, live crown length) in the beginning of the measurement period differed among treatments and blocks, data unification was made: increment values were used instead of measured values. To identify the effects of which treatments were significantly different, the Tukey Honestly Significant Difference (HSD) test (multiple comparison test) was applied for results with significant differences between treatments stated by RCBD analysis. Because of subsampling in the analysis of variance, it was not possible to use ready R formula to perform the Tukey test, therefore the test was applied according to the "Tukey Multiple Comparison Procedure" in Kutner et al. (2005).

Moreover, relationships between:

- diameter at breast height and height;
- diameter at breast height and live crown length;
- average live crown length and stand basal area;

- average height and stand volume;
- average live crown length and stand volume;
- average stand volume and average diameter;
- stand volume and stand basal area

were compared separately for treatments and years with use of Pearson correlation coefficient (called in following thesis also: Pearson's r, correlation coefficient or r).

Additionally, diagrams presenting diameter distributions for separate treatments in time were created.

4. Results

4.1 Average diameter at breast height

In all studied trials the average diameter at breast height and its increment were the smallest in control plots. In the Crane Lake and the Middle Branch East trials, both attributes increased with increasing thinning intensity. When it comes to the Atlantic Mine trial, pattern for diameter increment was similar to other trials, but additional thinning from below gave lower values than the every third row removal with crown thinning. However, the largest average diameter occurred for the thinning from below, due to removal of smaller trees. Nevertheless, the difference between treatments (excluding control plot) in mean DBH increment was non-significant for the Atlantic Mine and the Middle Branch East trials. In the Crane Lake trial mean delta diameter after treatment 2 (every third row removal with crown thinning in remaining rows) was significantly larger than for other treatments.

4.1.1 Atlantic Mine Thinning Trial

The growth of diameter at breast height is presented in the Fig. 4.1. Stands where removal of every third row plus thinning from below were applied maintained the highest diameter at breast height for the entire measurement period. Diameter increment (Fig. 4.2) maintained similar tendency over entire measurement period, with an exception of treatment 1, which had a highest value the year after the thinning, but then dropped below values of remaining treatments that were applied. Diameter increment in the control plot receded from values for remaining treatments in time.

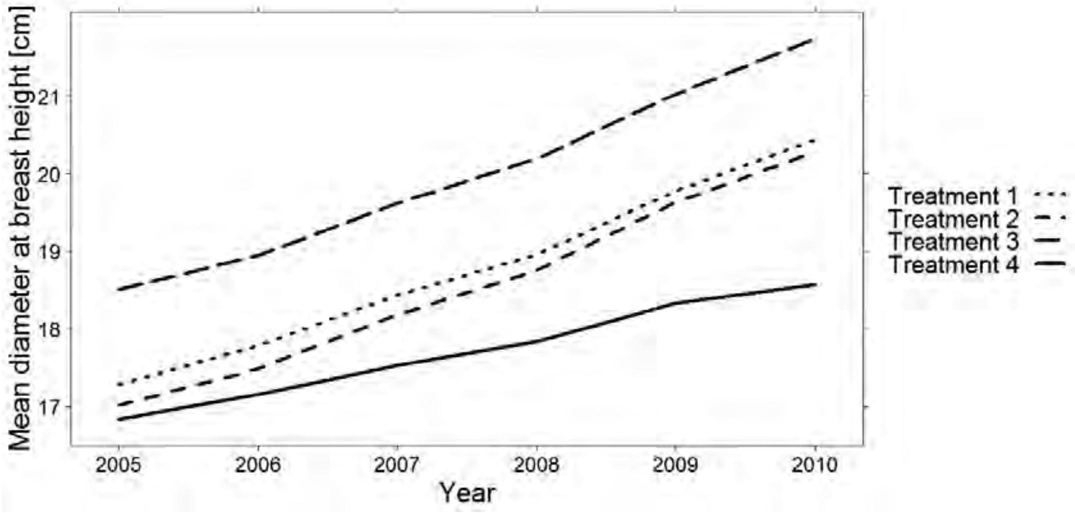

Fig. 4.1 Mean diameter at breast height in the Atlantic Mine. Lines represent treatments: 1- removal of every fifth row plus crown thinning, 2- removal of every third row plus crown thinning, 3- removal of every third row plus thinning from below, 4- no thinning (control plot).

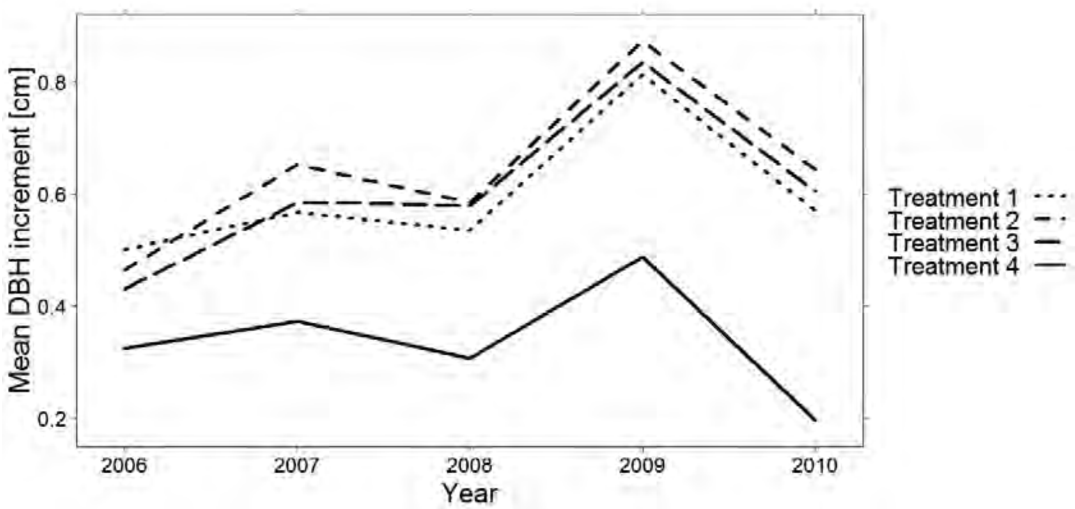

Fig. 4.2 Mean diameter increment in the Atlantic Mine. Lines represent treatments: 1- removal of every fifth row plus crown thinning, 2- removal of every third row plus crown thinning, 3- removal of every third row plus thinning from below, 4- no thinning (control plot).

The analysis of variance confirmed that the average diameter increment differed significantly between treatments in every year of measurements (Table 4.1). The results of multiple comparisons test are presented in Fig. 4.3. There was no significant difference between applied treatments in their effect on diameter increment, but in most cases they were significantly larger than the mean increment in the control plot.

Table 4.1
The analysis of variance results for mean diameter increment in the Atlantic Mine.

Year	Source	Degrees of freedom	Sum of squares	MSE (mean square error)	F value	Pr (>F)	Bartlett test (p value)
2006	Treatments	3	0.1569	0.0523	18.6823	**9.20E-07***	0.8925
	Block	2	0.0406	0.0203	7.2492	0.00302	
	Residuals	27	0.0756	0.0028			
2007	Treatments	3	0.3502	0.1167	35.2579	**1.76E-09***	0.5599
	Block	2	0.0028	0.0014	0.4196	0.6615	
	Residuals	27	0.0894	0.0033			
2008	Treatments	3	0.4171	0.1390	33.1055	**3.43E-09***	0.8744
	Block	2	0.0744	0.0372	8.8615	0.0011	
	Residuals	27	0.1134	0.0042			
2009	Treatments	3	0.7975	0.2658	56.6594	**8.88E-12***	0.0207
	Block	2	0.0372	0.0186	3.9691	0.03082	
	Residuals	27	0.1267	0.0047			
2010	Treatments	3	1.0545	0.3515	42.5362	**2.29E-10***	0.6326
	Block	2	0.0022	0.0011	0.1345	0.8748	
	Residuals	27	0.2231	0.0083			

*significant on the significance level α=0.05

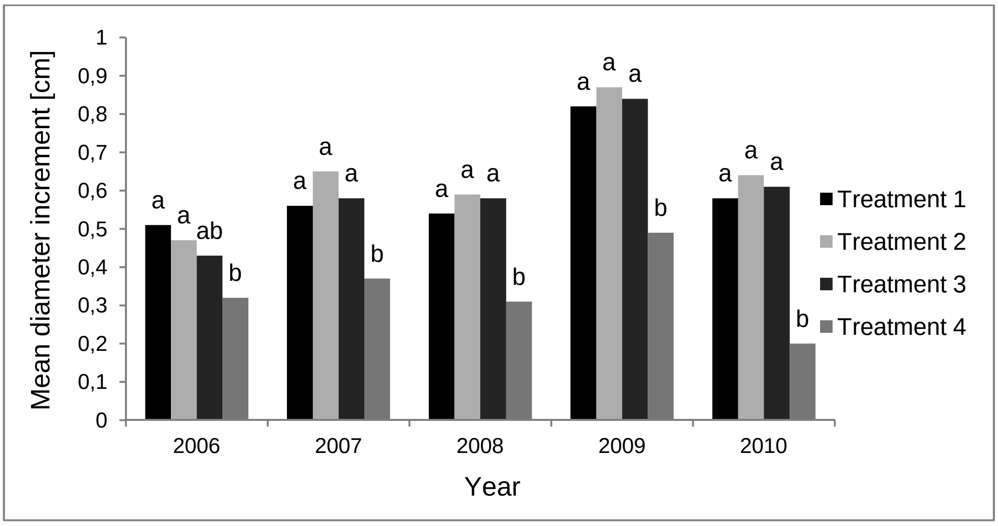

Fig. 4.3 Mean diameter increment in the Atlantic Mine for different years and treatments: 1- removal of every fifth row plus crown thinning, 2- removal of every third row plus crown thinning, 3- removal of every third row plus thinning from below, 4- no thinning (control plot). Different letters above bars indicate significant differences between means according to the Tukey test.

4.1.2 Crane Lake Thinning Trial

Differences between treatments in mean diameter at breast height increased in time (Fig. 4.6). Diameter increments changed in time on a rate similar for all treatments (Fig. 4.5).

The ANOVA confirmed the hypothesis about the relevant difference between mean diameter increment in plots where different thinning treatments were applied. Important difference between treatments occurred in every year of measurements (Table 4.2). The Tukey multiple comparison test confirmed significant differences between control plot and thinned plots for all years and additionally relevant difference between treatment 1 and 2 for years: 2007-2010 (Fig. 4.6). Significantly larger increments were the result of the most intensive treatment, every third row removal with thinning from above in remaining rows, for these years.

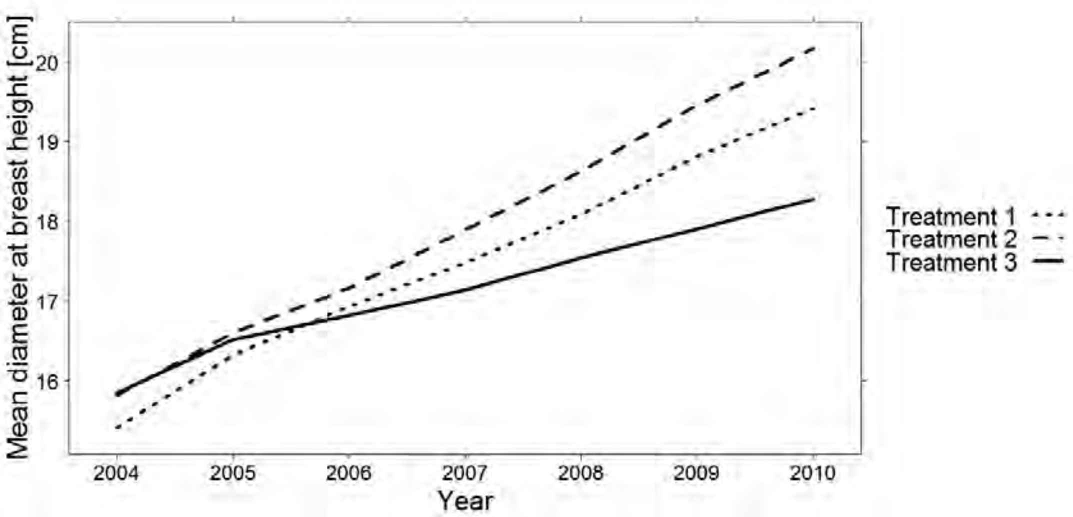

Fig. 4.4 Mean diameter at breast height in the Crane Lake. Lines represent treatments: 1- removal of every third row, 2- removal of every third row and crown thinning, 3- no thinning (control plot).

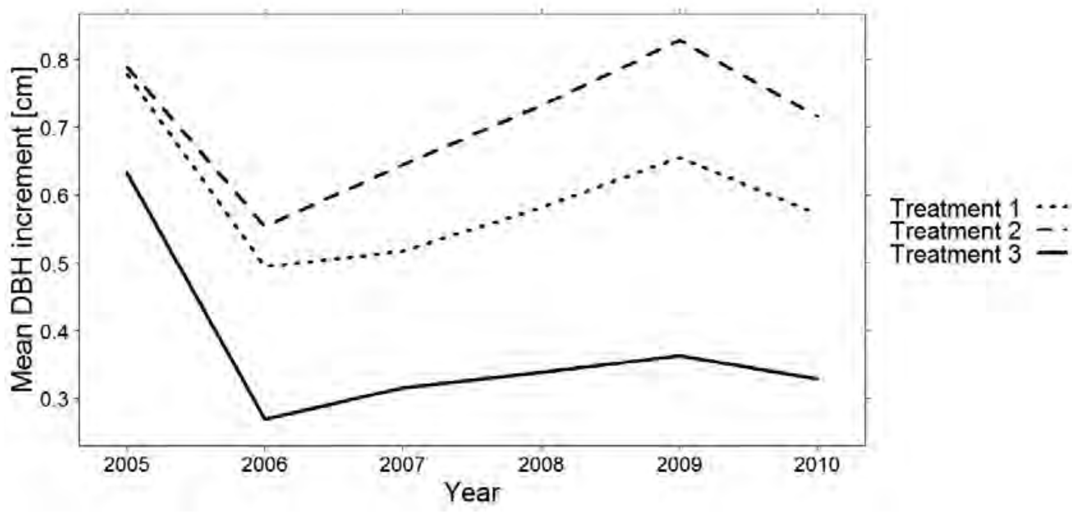

Fig. 4.5 Mean diameter increment in the Crane Lake. Lines represent treatments: 1- removal of every third row, 2- removal of every third row and crown thinning, 3- no thinning (control plot).

Table 4.2
The analysis of variance results for diameter increment in the Crane Lake.

Year	Source	Degrees of freedom	Sum of squares	MSE (mean square error)	F value	Pr (>F)	Bartlett test (p value)
	Treatment	2	0.2510	0.1255	23.0095	**2.836e-07***	
2005	Block	3	0.0267	0.0089	1.6316	0.1981	0.4907
	Residuals	38	0.2072	0.0055			
	Treatment	2	0.7041	0.3521	61.9056	**1.108e-12***	
2006	Block	3	0.0415	0.0138	2.4315	0.08001	0.1421
	Residuals	38	0.2161	0.0057			
	Treatment	2	0.8655	0.4328	106.246	**2.747e-16***	
2007	Block	3	0.0027	0.0009	0.2199	0.882	0.1067
	Residuals	38	0.1548	0.0041			
	Treatment	2	1.2538	0.6269	142.858	**<2e-16***	
2008	Block	3	0.0204	0.0068	1.5493	0.2176	0.6678
	Residuals	38	0.1668	0.0044			
	Treatment	2	1.7042	0.8521	159.776	**<2e-16***	
2009	Block	3	0.0136	0.0045	0.8476	0.4765	0.1799
	Residuals	38	0.202	0.0053			
	Treatment	2	1.1949	0.5974	144.585	**<2e-16***	
2010	Block	3	0.0213	0.0071	1.7181	0.1796	0.1691
	Residuals	38	0.1570	0.0041			

*significant on the significance level α=0.05

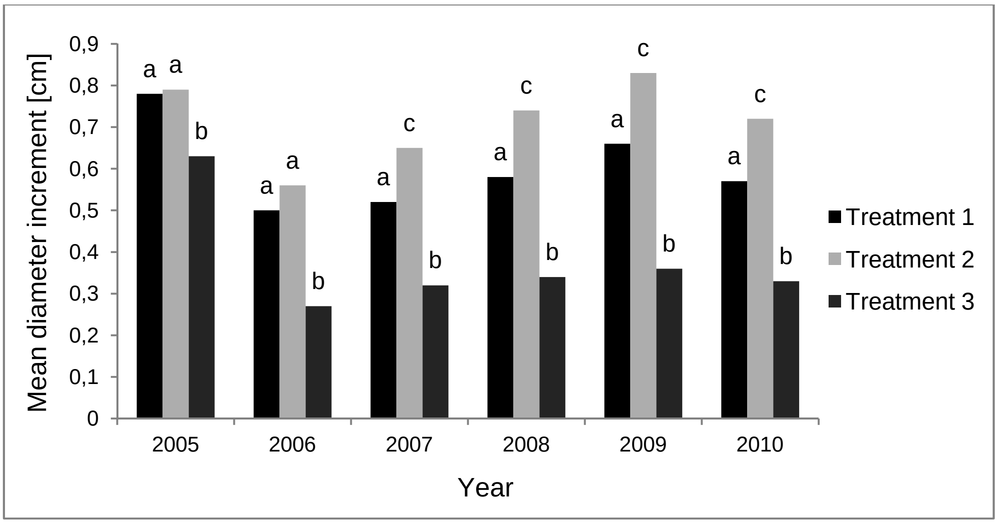

Fig. 4.6 Mean diameter increment in the Crane Lake for different years and treatments: 1- removal of every third row, 2- removal of every third row and crown thinning, 3- no thinning (control plot). Different letters above bars indicate significant differences between means according to the Tukey test.

4.1.3 Middle Branch East Thinning Trial

Average diameter at breast height (Fig. 4.7) and its increment (Fig. 4.8) increased with an increase in number of trees removed in treatment. Also spread between average diameter for different treatments increased in time.

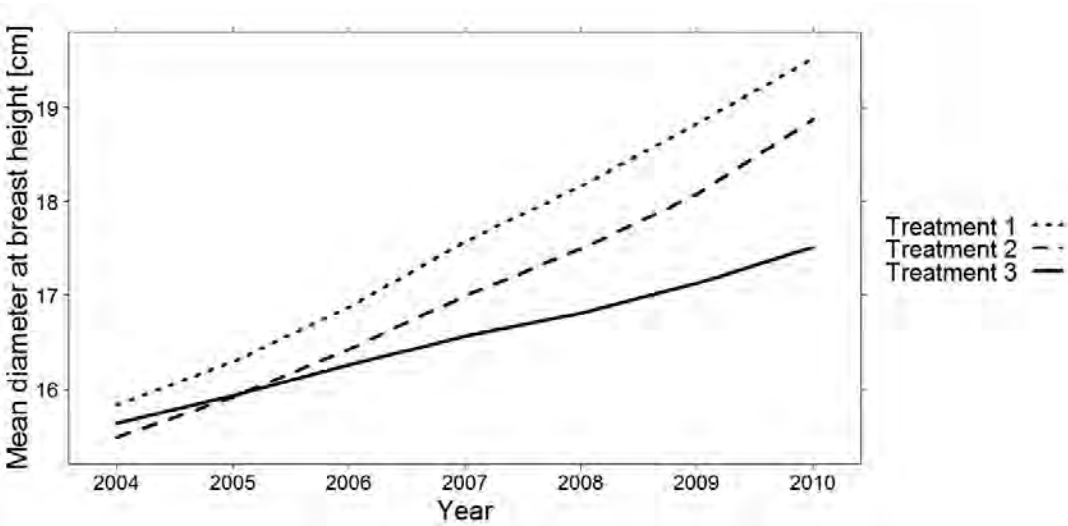

Fig. 4.7 Mean diameter at breast height in the Middle Branch East. Lines represent treatments: 1- removal of every third row plus one in three dominant or codominant trees, 2- removal of every third row plus one in five dominant or codominant trees, 3- no thinning (control plot).

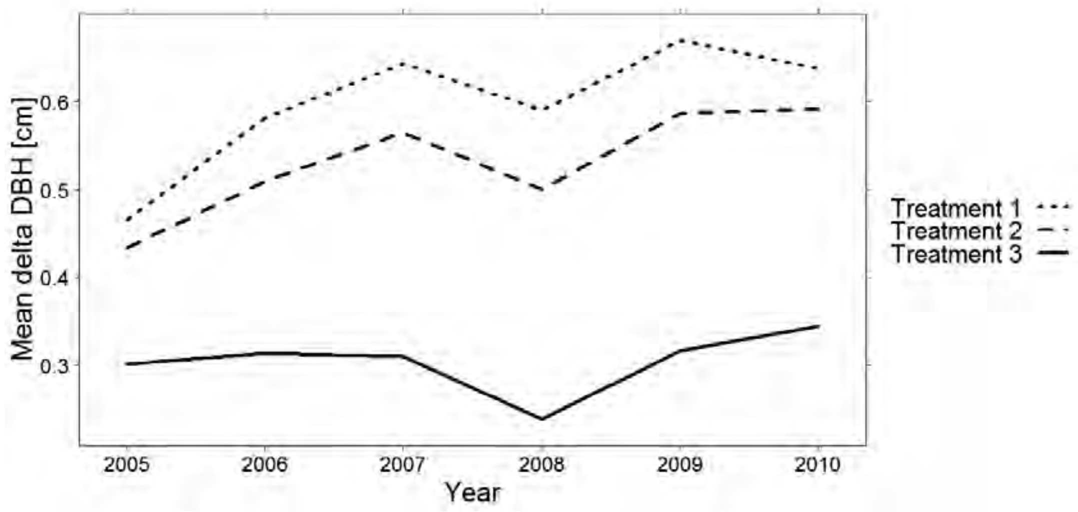

Fig. 4.8 Mean diameter increment in the Middle Branch East. Lines represent treatments: 1- removal of every third row plus one in three dominant or codominant trees, 2- removal of every third row plus one in five dominant or codominant trees, 3- no thinning (control plot).

The results of the analysis of variance confirmed hypothesis that the thinning type had a significant influence on the diameter increment (Table 4.3). The Tukey test showed non- significant difference between applied treatments in their effect on mean diameter increment (Fig. 4.9). However mean DBH increment was significantly larger for both thinning treatments compared to the control plot.

Table 4.3
The analysis of variance results for DBH increment in the Middle Branch East

Year	Source	Degrees of freedom	Sum of squares	MSE (mean square error)	F value	Pr (>F)	Bartlett test (p value)
	Treatments	2	0.179242	0.089621	58.5253	**9.976e-11***	
2005	Block	2	0.000921	0.000460	0.3006	0.7427	0.6042
	Residuals	28	0.042877	0.001531			
	Treatments	2	0.46495	0.232475	97.0713	**2.555e-13***	
2006	Block	2	0.03219	0.016094	6.7201	0.004133	0.1106
	Residuals	28	0.06706	0.002395			
	Treatments	2	0.73942	0.36971	55.8175	**1.699e-10***	
2007	Block	2	0.04795	0.02398	3.6197	0.03998	0.04163
	Residuals	28	0.18546	0.00662			
	Treatments	2	0.80056	0.40028	131.134	**6.039e-15***	
2008	Block	2	0.00757	0.00379	1.2407	0.3046	0.5774
	Residuals	28	0.08547	0.00305			
	Treatments	2	0.82141	0.41070	120.467	**1.759e-14***	
2009	Block	2	0.03344	0.01672	4.904	0.01493	0.8409
	Residuals	28	0.09546	0.00341			
	Treatments	2	0.58683	0.293416	139.344	**2.795e-15***	
2010	Block	2	0.00651	0.003255	1.546	0.2307	0.5774
	Residuals	28	0.05896	0.002106			

*significant for the significance level α=0.05

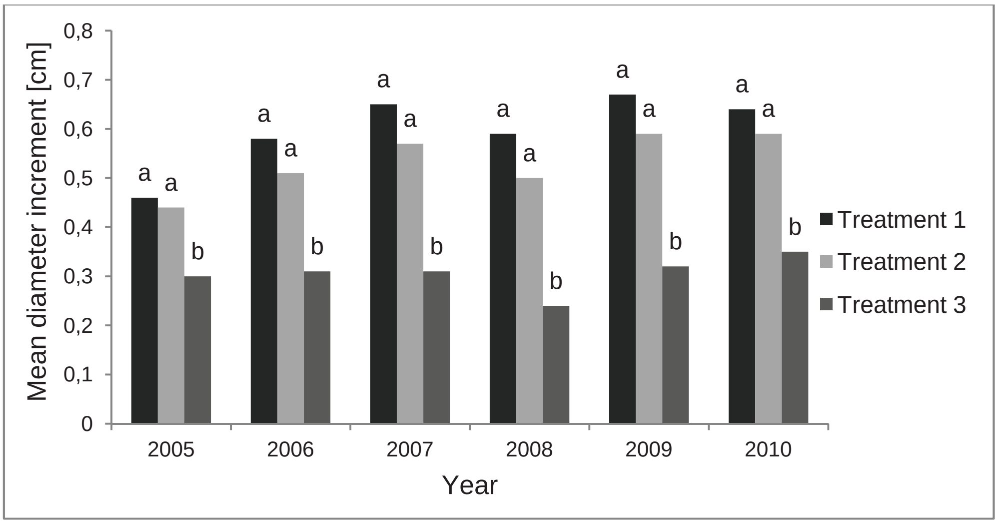

Fig. 4.9 Mean diameter increment in the Middle Branch East for different years and treatments: 1- removal of every third row plus one in three dominant or codominant trees, 2- removal of every third row plus one in five dominant or codominant trees, 3- no thinning (control plot). Different letters above bars indicate significant differences between means according to the Tukey test.

4.2 Diameter distribution

4.2.1 Atlantic Mine Thinning Trial

Diameter distributions were similar for treatments 1 and 2: the most abundant classes were the same for the entire measurement period, but the number of trees was lower for treatment 2 due to higher thinning intensity (Fig. 4.10). In the case of treatment 3, three classes (higher than in treatment 1 and 2 because of thinning from below) included most of the trees, while stocking in remaining classes was substantially smaller. Trees in the control plot moved towards normal distribution in time. Shift to larger diameter classes and spread to larger number of classes in time were pronounced especially for plots were thinnings were applied.

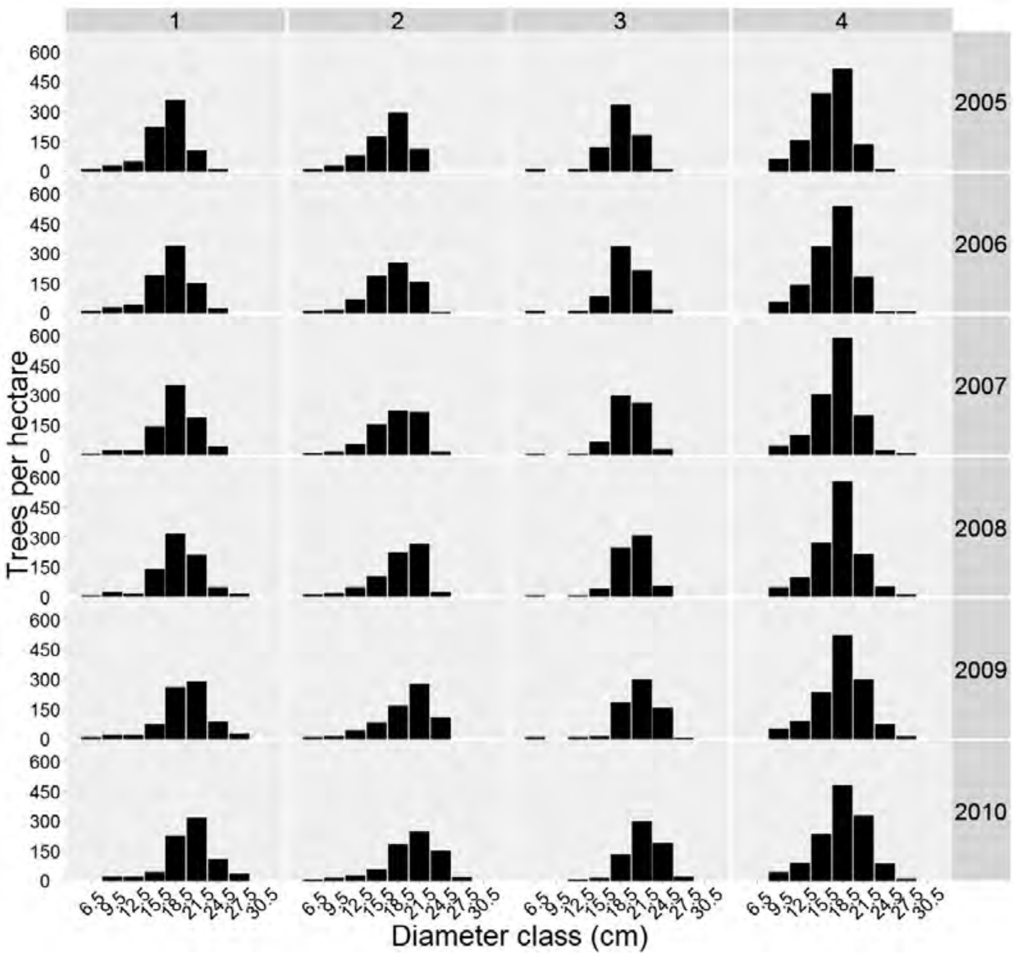

Fig. 4.10 Diameter distribution in time in the Atlantic Mine. Columns represent treatments: 1- removal of every fifth row plus crown thinning, 2- removal of every third row plus crown thinning, 3- removal of every third row plus thinning from below, 4- no thinning (control plot). Numbers on the x-axis mean centers of 3 cm classes.

4.2.2 Crane Lake thinning trial

After the row thinning (treatment 1) diameters maintained relatively normal distribution for the entire measurement period (Fig. 4.11). Due to removal of trees from all diameter classes in this treatment, diameter distribution was similar to the control plot. For treatment 2, where, apart from mechanical, thinning from above was applied, number of trees in larger diameter classes decreased compared to simple row thinning. Shift to larger diameter classes and spread to larger number of classes in time were pronounced especially for plots were thinnings were applied.

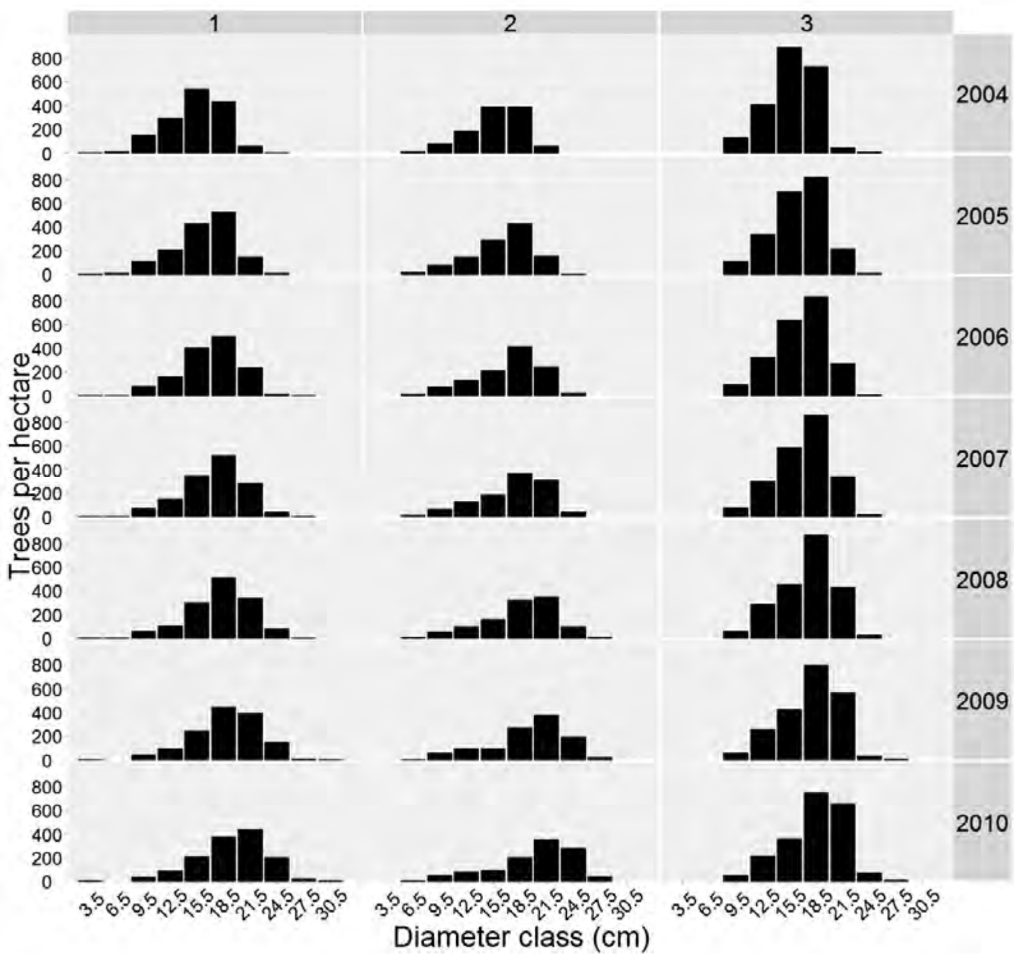

Fig. 4.11 Diameter distribution in time in the Crane Lake. Columns represent treatments: 1-removal of every third row, 2 removal of every third row and crown thinning, 3- no thinning (control plot). Numbers on the x-axis mean centers of 3 cm classes.

4.2.3 Middle Branch East Thinning Trial

Diameter distributions were similar for thinning treatments 1 and 2 (Fig. 4.12), with larger number of trees for treatment 2. Skew towards smaller classes could be observed in the control plot in the initial years. However, number of trees in particular diameter classes moved towards normal distribution in following years. Shift to larger diameter classes and spread to larger number of classes in time were pronounced especially for plots were thinnings were applied.

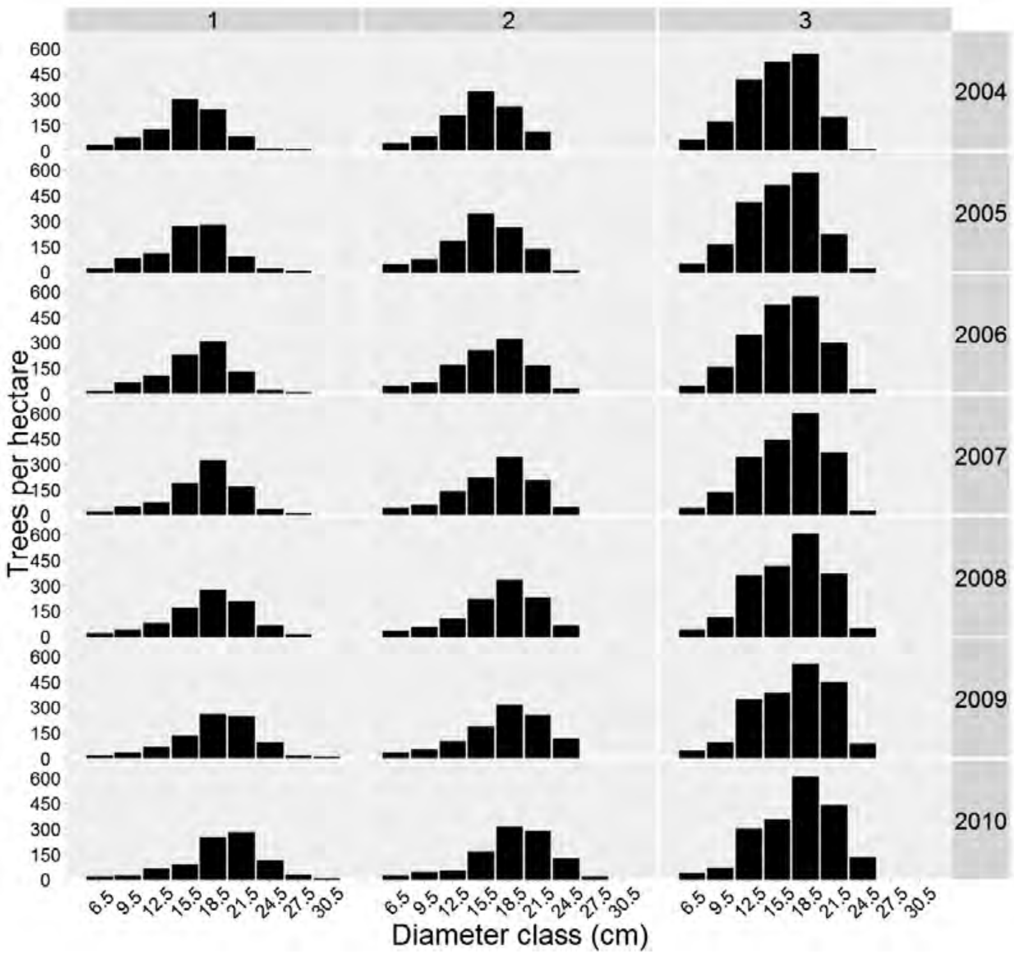

Fig. 4.12 Diameter distribution in time in the Middle Branch East. Columns represent treatments: 1- removal of every third row plus one in three dominant or codominant trees, 2- removal of every third row plus one in five dominant or codominant trees, 3- no thinning (control plot). Numbers on the x-axis mean centers of 3 cm classes.

4.3 Stand basal area

Average stand basal area (called further also “basal area”) in all trials decreased with increasing number of harvested trees, due to the “chainsaw effect” (Pelletler and Pitt 2008). Basal area maintained constant increasing trend over time. There was no straight pattern in basal area increment over time due to significant interactions between blocks and treatments. Though, the year after the harvest BA increment was the smallest for the most intensive treatments. Except the first year after the harvest, when basal area increment was significantly larger in controls compared to remaining thinnings, there was no statistically significant difference between treatments in all years when relevant blocks-treatments interaction did not occur.

4.3.1 Atlantic Mine Thinning Trial

As a result of the harvest in 2006, basal area decreased by 45% and 48% for treatments 1 and 2, respectively. The smallest decrease, by 44%, was related to the thinning from below treatment (Fig. 4.13).

According to (Fig. 4.14) basal area was obviously the largest in plots where no treatment was applied. However its increment in control plot was the largest among treatments in the beginning and the smallest in the end of the measurement period (Fig. 4.15). There was no clear trend in basal area increment, however substantial decline after 2009 can be observed for all treatments, especially for the control plot.

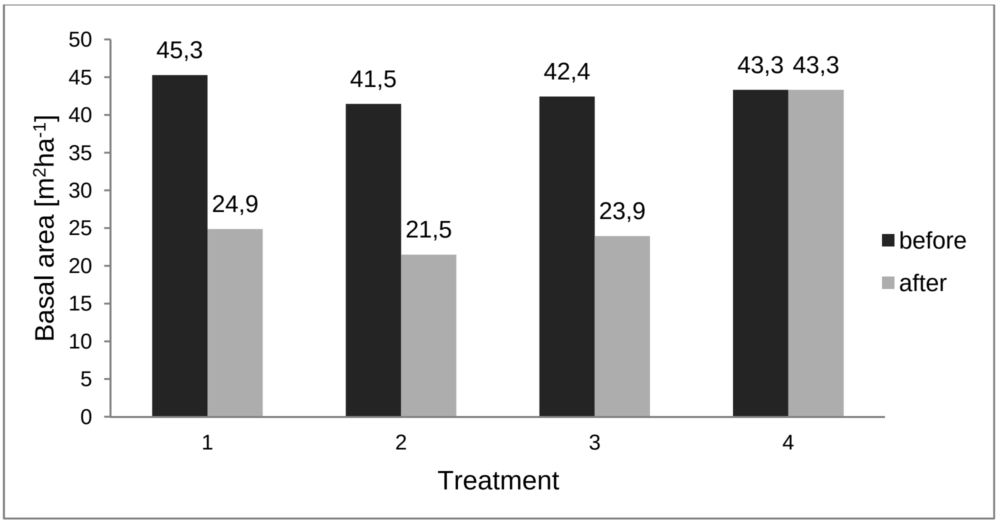

Fig. 4.13 Stand basal area in the Atlantic Mine before and after the harvest in 2005 for different thinning treatments: 1- removal of every fifth row plus crown thinning, 2- removal of every third row plus crown thinning, 3- removal of every third row plus thinning from below, 4- no thinning (control plot).

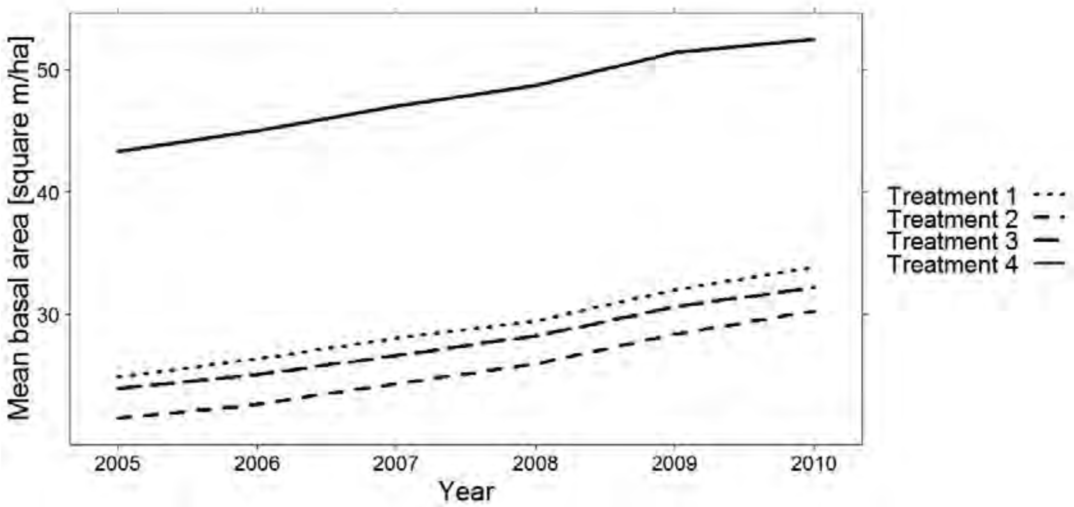

Fig. 4.14 Mean basal area in the Atlantic Mine. Lines represent treatments: 1- removal of every fifth row plus crown thinning, 2- removal of every third row plus crown thinning, 3- removal of every third row plus thinning from below, 4- no thinning (control plot).

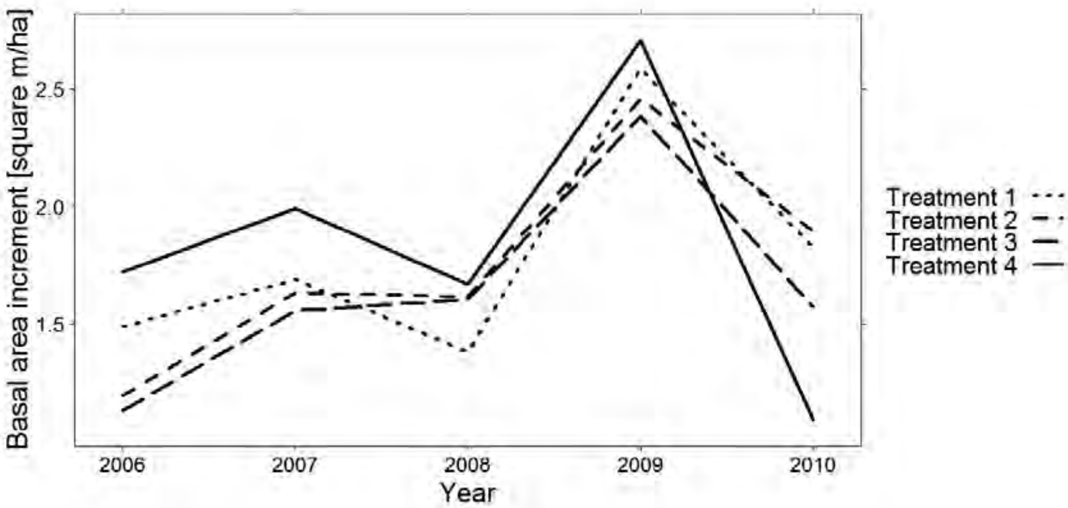

Fig. 4.15 Mean basal area increment in the Atlantic Mine. Lines represent treatments: 1- removal of every fifth row plus crown thinning, 2- removal of every third row plus crown thinning, 3- removal of every third row plus thinning from below, 4- no thinning (control plot).

According to the analysis of variance results (Table 4.4), there was a significant effect of thinning type on average basal area change in 2006 and 2010. The Tukey test confirmed significant difference between control plot and treatments 1 and 2 (the heaviest thinnings) the year after the harvest (Fig. 4.16). Multiple comparison test was not performed for 2010 due to significant blocks-treatments interaction (Fig. 9.1).

Table 4.4
The analysis of variance results for basal area increment in the Atlantic Mine.

Year	Source	Degrees of freedom	Sum of squares	MSE (mean square error)	F value	Pr (>F)	Bartlett test (p value)
	Treatments	3	1.9390	0.6463	17.5578	**1.60E-06***	
2006	Block	2	0.1314	0.0657	1.7841	.1872	0.1391
	Residuals	27	0.9939	0.0368			
	Treatments	3	0.9536	0.3179	2.6002	0.0727	
2007	Block	2	0.1218	0.0609	0.498	0.6132	0.0318
	Residuals	27	3.3005	0.1222			
	Treatments	3	0.4918	0.1640	0.5755	0.63608	
2008	Block	2	2.0593	1.0297	3.6143	0.04066	0.0004
	Residuals	27	7.6919	0.2849			
	Treatments	3	0.5322	0.1774	2.0387	0.1321	
2009	Block	2	0.3877	0.1939	2.2280	0.1272	0.2412
	Residuals	27	2.3493	0.0870			
	Treatments	3	3.1952	1.0651	4.7755	**0.008504***	
2010	Block	2	0.3559	0.1779	0.7978	0.460661	0.0456
	Residuals	27	6.0218	0.2230			

*significant on the significance level α=0.05

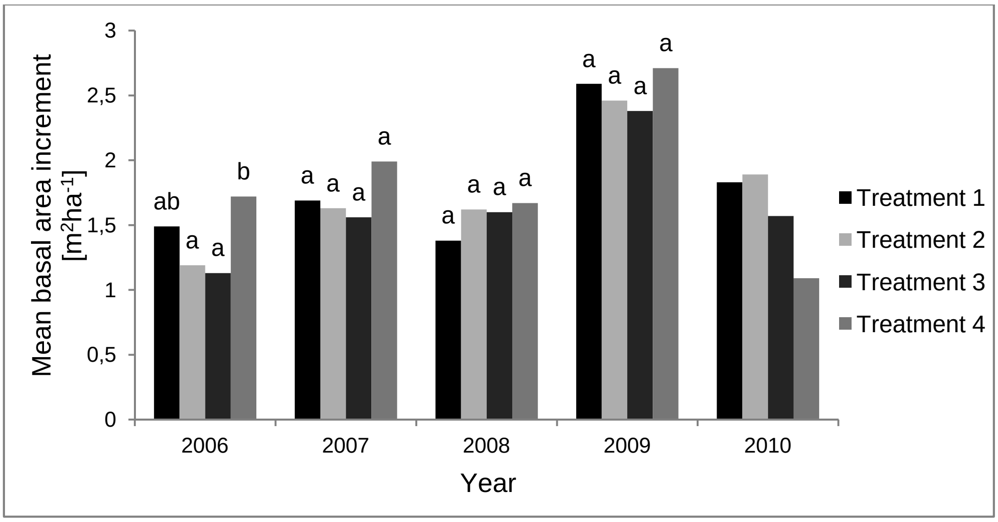

Fig. 4.16 Basal area increment in the Atlantic Mine for different years and treatments: 1- removal of every fifth row plus crown thinning, 2- removal of every third row plus crown thinning, 3- removal of every third row plus thinning from below, 4- no thinning (control plot). Different letters above bars indicate significant differences between means according to the Tukey test. Lack of letters above bars indicates significant blocks- treatments interaction.

4.3.2 Crane Lake thinning trial

As a result of the harvest in 2004, basal area decreased by 30% and 47% for treatments 1 and treatment 2 respectively (Fig. 4.17).

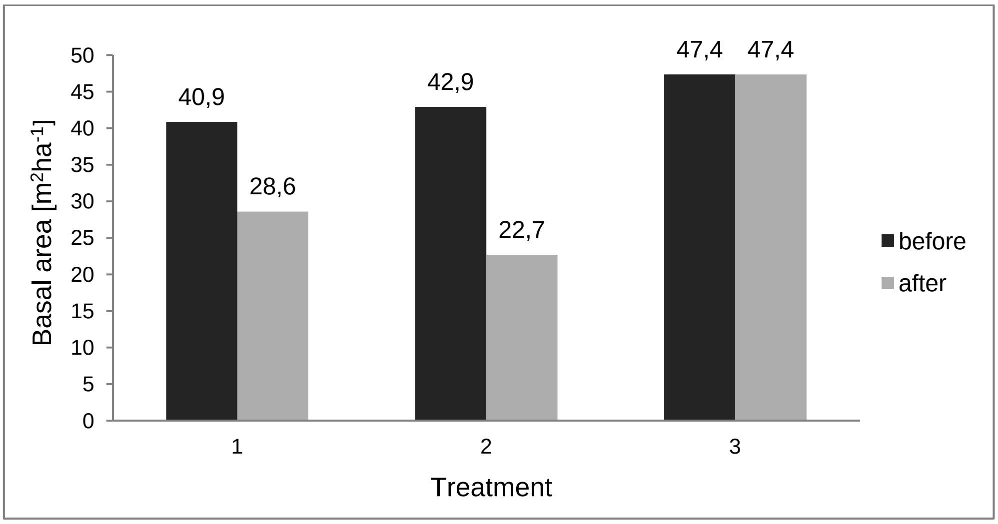

Fig. 4.17 Stand basal area in the Crane Lake before and after the harvest in 2004 for different thinning treatments: 1- removal of every third row, 2- removal of every third row and crown thinning, 3- no thinning (control plot).

Average basal area decreased with increasing thinning intensity (Fig. 4.18). When it comes to mean basal area increment, trends were basically reversed, with an exception of the first year after the harvest (Fig. 4.19), when a pattern was similar to stand basal area growth.

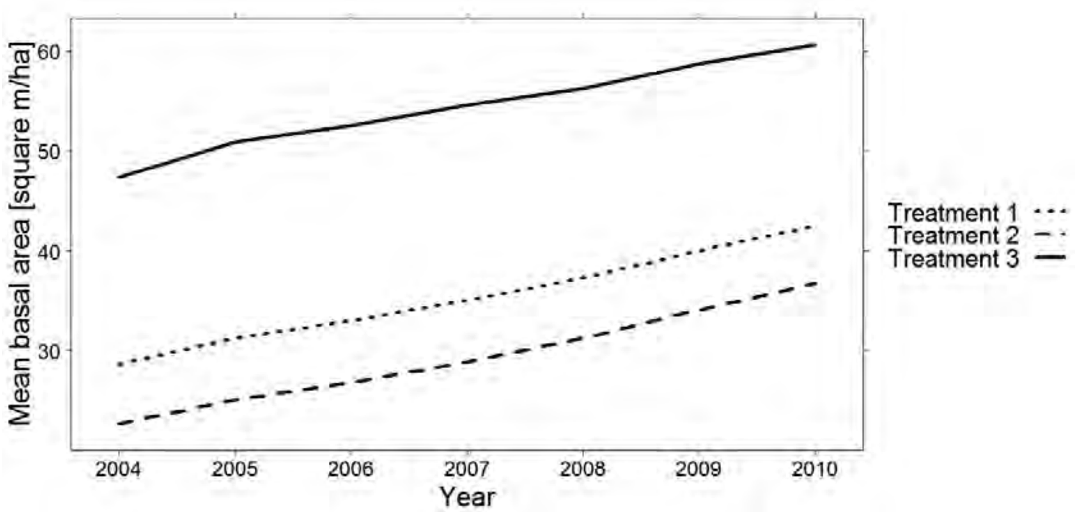

Fig. 4.18 Mean basal area in the Crane Lake. Lines represent treatments: 1- removal of every third row, 2- removal of every third row and crown thinning, 3- no thinning (control plot).

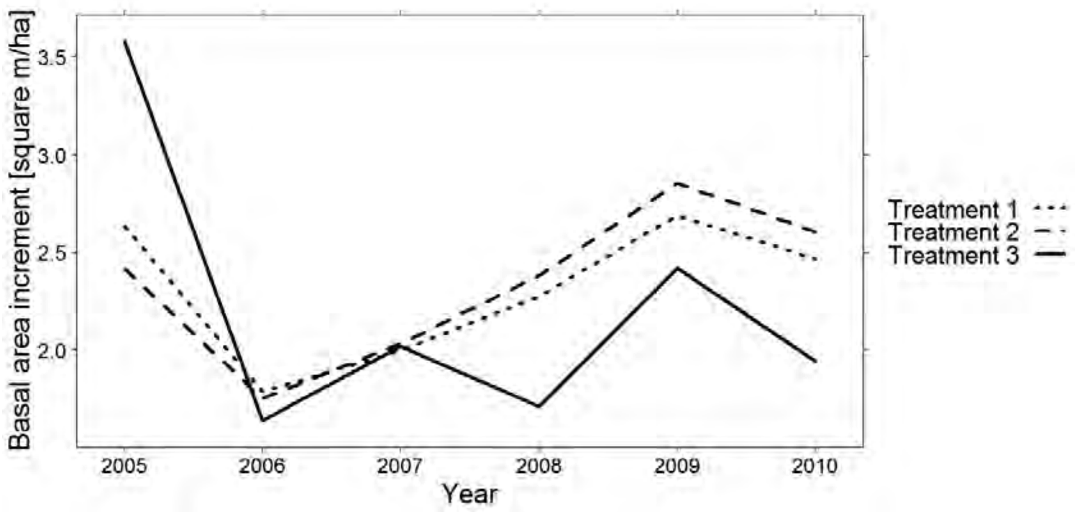

Fig. 4.19 Mean basal area increment in the Crane Lake. Lines represent treatments: 1- removal of every third row, 2- removal of every third row and crown thinning, 3- no thinning (control plot).

The results of the analysis of variance (Table 4.5) show that thinning type had a significant influence on the basal area increment in the years: 2005, 2008, 2009 and 2010. The Tukey test confirmed significant differences between all treatments in 2005 (Fig. 4.20). The HSD test was not performed for years 2008, 2009 and 2010 because of significant blocks-treatments interaction (Fig. 9.1).

Table 4.5
The analysis of variance results for basal area increment in the Crane Lake.

Year	Source	Degrees of freedom	Sum of squares	MSE (mean square error)	F value	Pr (>F)	Bartlett test (p value)
2005	Treatment	2	11.8095	5.9047	21.5546	**5.54e-07***	0.0193
	Block	3	0.8425	0.2808	1.0252	0.3923	
	Residuals	38	10.4099	0.2739			
2006	Treatment	2	0.2003	0.1001	0.8131	0.45103	0.1857
	Block	3	1.0268	0.3423	2.7794	0.05419	
	Residuals	38	4.6794	0.1231			
2007	Treatment	2	0.0082	0.0041	0.0489	0.9523	0.2553
	Block	3	0.3275	0.1092	1.2986	0.289	
	Residuals	38	3.1944	0.0840			
2008	Treatment	2	4.4302	2.2151	6.8886	**0.002801**	0.0007
	Block	3	0.8393	0.2797	0.8700	0.465086	
	Residuals	38	12.2192	0.3216			
2009	Treatment	2	1.4221	0.7111	8.2247	**0.001077***	0.2687
	Block	3	1.4401	0.4800	5.5523	0.002923	
	Residuals	38	3.2852	0.0865			
2010	Treatment	2	3.7503	1.8751	8.0031	**0.001257***	6.185e-05
	Block	3	0.7622	0.2541	1.0843	0.367383	
	Residuals	38	8.9035	0.2343			

*significant on the significance level α=0.05

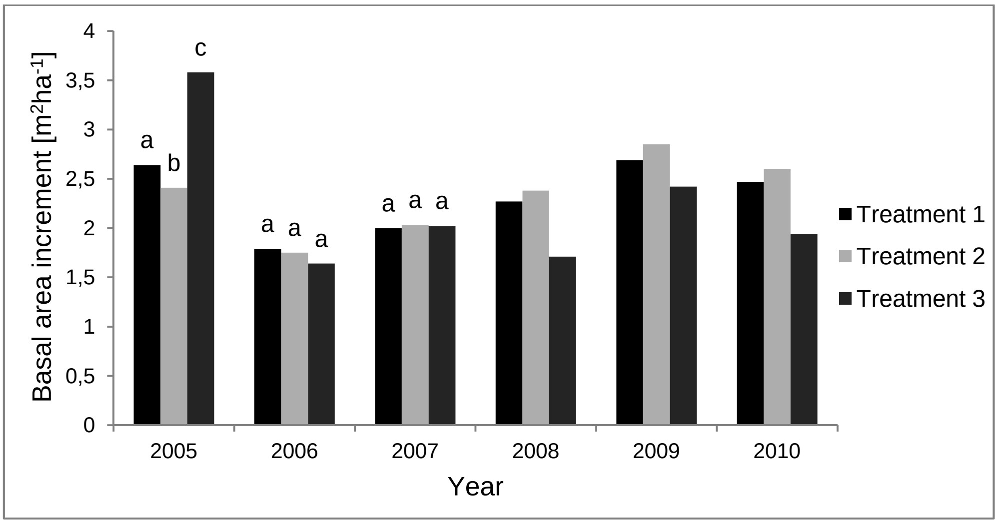

Fig. 4.20 Mean basal area increment in the Crane Lake for different years and treatments: 1- removal of every third row, 2- removal of every third row and crown thinning, 3- no thinning (control plot). Different letters above bars indicate significant differences between means according to the Tukey test. Lack of letters above bars indicates significant blocks- treatments interaction.

4.3.3 Middle Branch East Thinning Trial

After the harvest on 2004, thinning treatments: 1 and 2 decreased initial basal area on similar rate: by 44% and by 42% respectively (Fig. 4.21).

According to Fig. 4.22, stand basal area decreased with increasing number of harvested trees. The same tendency occurred for basal area increment for large part of measurement period, except substantial decrease for all treatments in 2008 (Fig. 4.23).

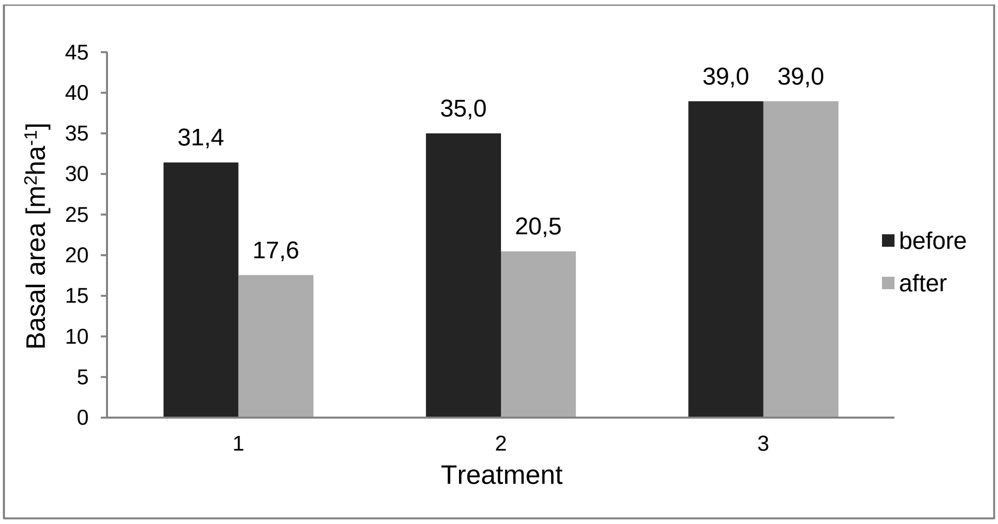

Fig. 4.21 Stand basal area in the Middle Branch East before and after the harvest in 2004 for different thinning treatments: 1- removal of every third row plus one in three dominant or codominant trees, 2- removal of every third row plus one in five dominant or codominant trees, 3- no thinning (control plot).

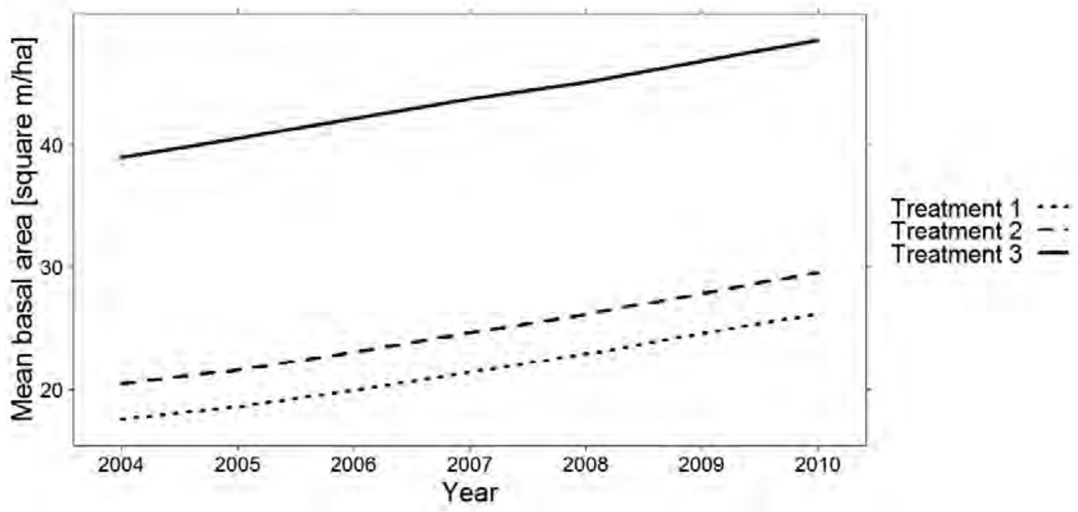

Fig. 4.22 Mean basal area in the Middle Branch East. Lines represent treatments: 1- removal of every third row plus one in three dominant or codominant trees, 2- removal of every third row plus one in five dominant or codominant trees, 3- no thinning (control plot).

The analysis of variance confirmed the hypothesis about significant difference between treatments in terms of their influence on basal area increment for years 2005 and 2006 (Table 4.6). However, because of important interactions between blocks and treatments in 2006 (Fig. 9.1), the Tukey test was performed only for the year 2005, and showed relevant difference between treatments: 1 and 3 (Fig. 4.24).

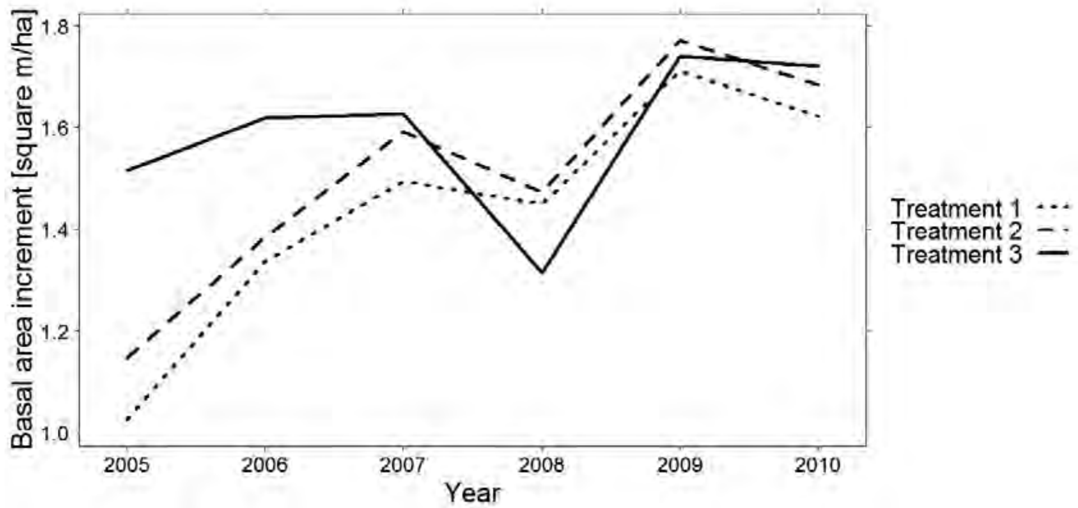

Fig. 4.23 Mean basal area increment in the Middle Branch East. Lines represent treatments: 1- removal of every third row plus one in three dominant or codominant trees, 2- removal of every third row plus one in five dominant or codominant trees, 3- no thinning (control plot).

Table 4.6
The analysis of variance results for basal increment area in the Middle Branch East.

Year	Source	Degrees of freedom	Sum of squares	MSE (mean square error)	F value	Pr (>F)	Bartlett test (p value)
2005	Treatments	2	1.5608	0.7804	20.5784	**3.18E-06**	0.7127
	Block	2	0.0042	0.0021	0.0556	0.9461	
	Residuals	28	1.0619	0.0379			
2006	Treatments	2	0.5454	0.2727	7.0584	**0.003295**	0.09867
	Block	2	0.3997	0.1998	5.1729	**0.012251**	
	Residuals	28	1.0817	0.0386			
2007	Treatments	2	0.1148	0.0574	0.7849	0.4660	0.2358
	Block	2	0.3455	0.1727	2.3618	0.1128	
	Residuals	28	2.0478	0.0731			
2008	Treatments	2	0.1776	0.0888	1.9170	0.1659	0.2987
	Block	2	0.0713	0.0356	0.7692	0.4729	
	Residuals	28	1.2972	0.0463			
2009	Treatments	2	0.0221	0.0110	0.1375	0.8721	0.679
	Block	2	0.3924	0.1962	2.4473	0.1048	
	Residuals	28	2.2449	0.0802			
2010	Treatments	2	0.0602	0.0301	0.1923	0.8261	0.1996
	Block	2	0.0010	0.0005	0.0031	0.9969	
	Residuals	28	4.3814	0.1565			

*significant on the significance level α=0.05

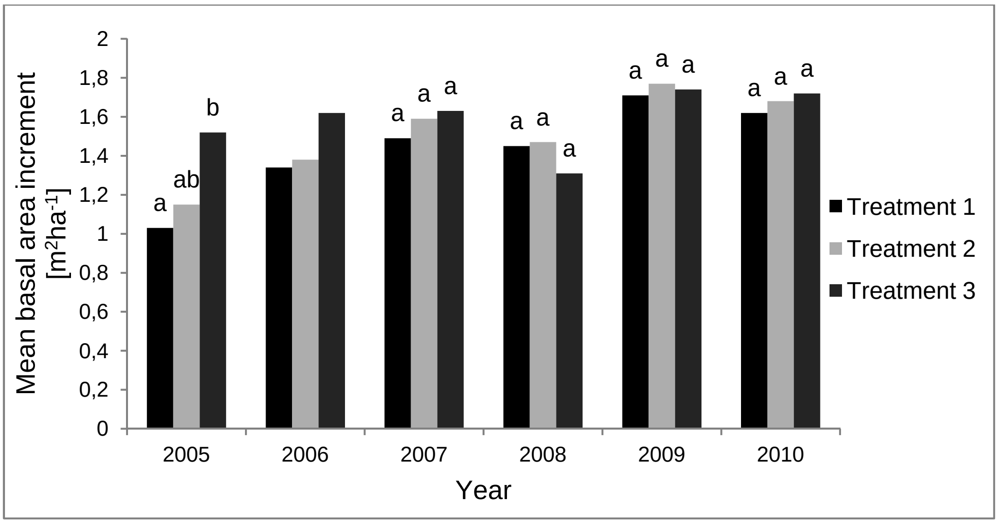

Fig. 4.24 Mean basal area increment in the Middle Branch East for different years and treatments: 1- removal of every third row plus one in three dominant or codominant trees, 2- removal of every third row plus one in five dominant or codominant trees, 3- no thinning (control plot). Different letters above bars indicate significant differences between means according to Tukey test. Lack of letters above bars indicates significant blocks- treatments interaction.

4.4 Average height

There was basically no clear effect of thinning type on average tree height and its increment. Alternative thinning intensities affected height growth on different rates in all trials. Nevertheless there was substantial decline, especially for height increment, in 2008.

4.4.1 Atlantic Mine Thinning Trial

The average height did not differ substantially between treatments, but it was the largest for the plots where thinning from below was applied (Fig. 4.25). The reason for this difference is that suppressed and lower trees were removed in this treatment. The largest height increment was observed in the control plot for the whole measurement period (Fig. 4.26).

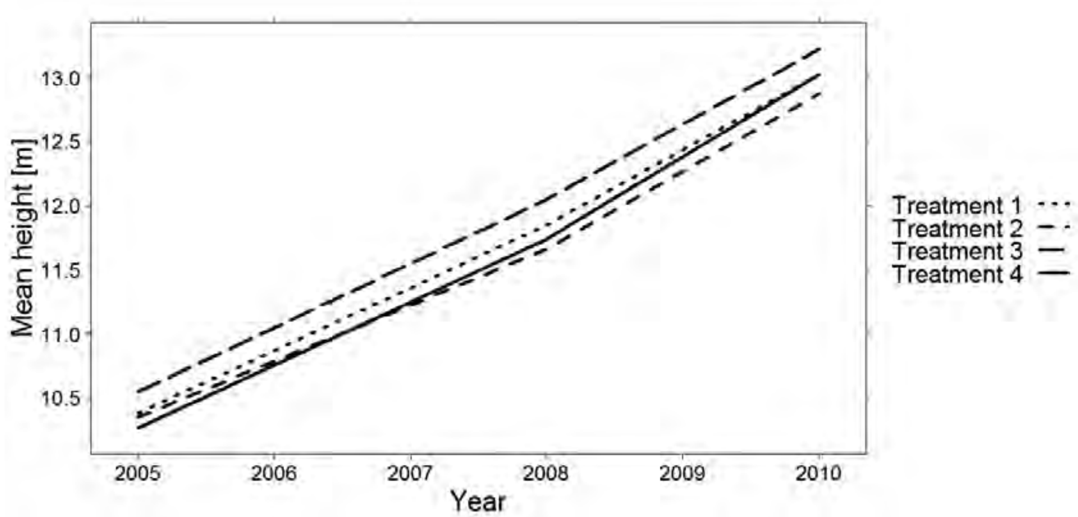

Fig. 4.25 Mean tree height in the Atlantic Mine. Lines represent treatments: 1- removal of every fifth row plus crown thinning, 2- removal of every third row plus crown thinning, 3- removal of every third row plus thinning from below, 4- no thinning (control plot).

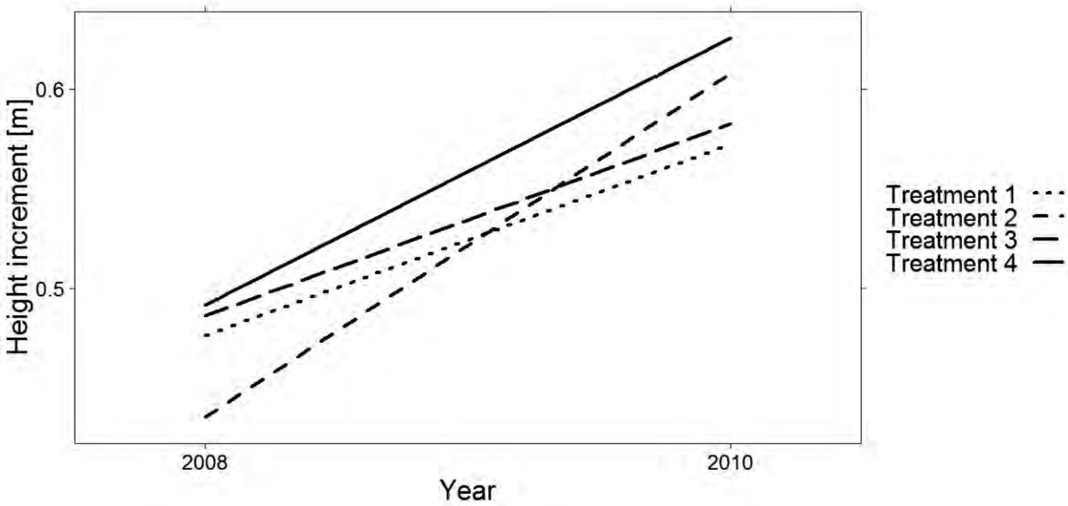

Fig. 4.26 Mean 1-year height increment in the Atlantic Mine. Lines represent treatments: 1- removal of every fifth row plus crown thinning, 2- removal of every third row plus crown thinning, 3- removal of every third row plus thinning from below, 4- no thinning (control plot).

The analysis of variance confirmed the null hypothesis about no significant difference between treatments in terms of their influence on mean tree height increment (Table 4.7, Fig. 4.27).

Table 4.7
The analysis of variance results for tree height increment in the Atlantic Mine.

Year	Source	Degrees of freedom	Sum of squares	MSE (mean square error)	F value	Pr (>F)	Bartlett test (p value)
	Treatments	3	0.1486	0.0495	2.8245	0.05754	
2008	Block	2	0.0739	0.0370	2.1078	0.14105	0.4483
	Residuals	27	0.4734	0.0175			
	Treatments	3	0.0542	0.0181	0.6737	0.57566	
2010	Block	2	0.2324	0.1162	4.3303	0.02338	0.1745
	Residuals	27	0.7245	0.0268			

*significant on the significance level α=0.05

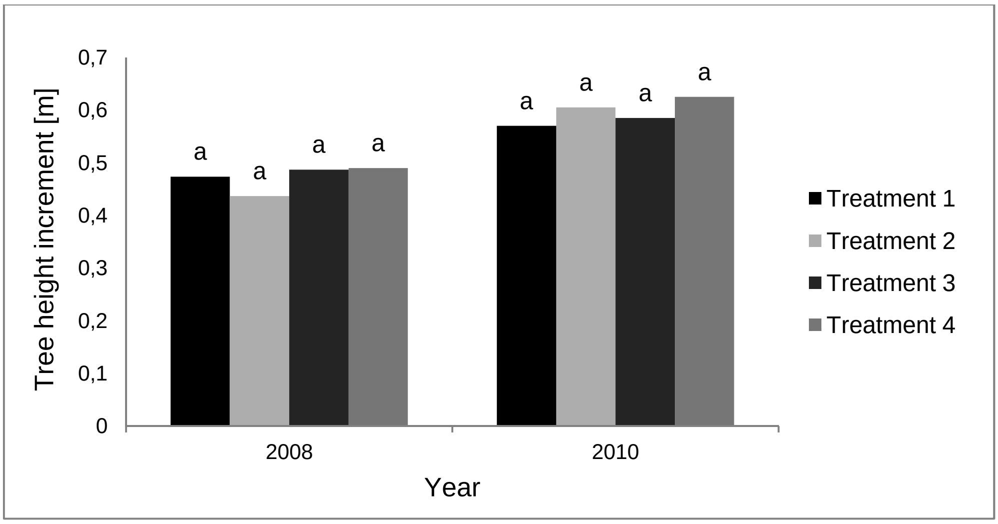

Fig. 4.27 Mean 1-year tree height increment in the Atlantic Mine for different years and treatments: 1- removal of every fifth row plus crown thinning, 2- removal of every third row plus crown thinning, 3- removal of every third row plus thinning from below, 4- no thinning (control plot). The same letters above bars indicate non-significant difference between means.

4.4.2 Crane Lake thinning trial

The average tree height did not differ substantially among treatments. Nevertheless, during entire measurement period, the average tree height tended to be the largest in control plot (Fig. 4.28). Average height increment had different tendencies in alternative treatments (Fig. 4.29, Fig. 4.30).

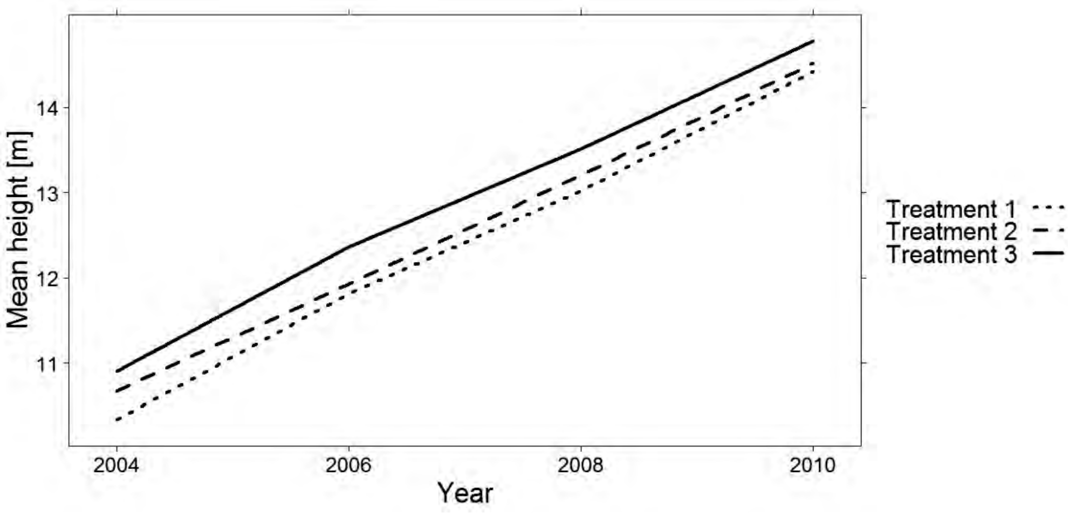

Fig. 4.28 Mean tree height in the Crane Lake. Lines represent treatments: 1- removal of every third row, 2- removal of every third row and crown thinning, 3- no thinning (control plot).

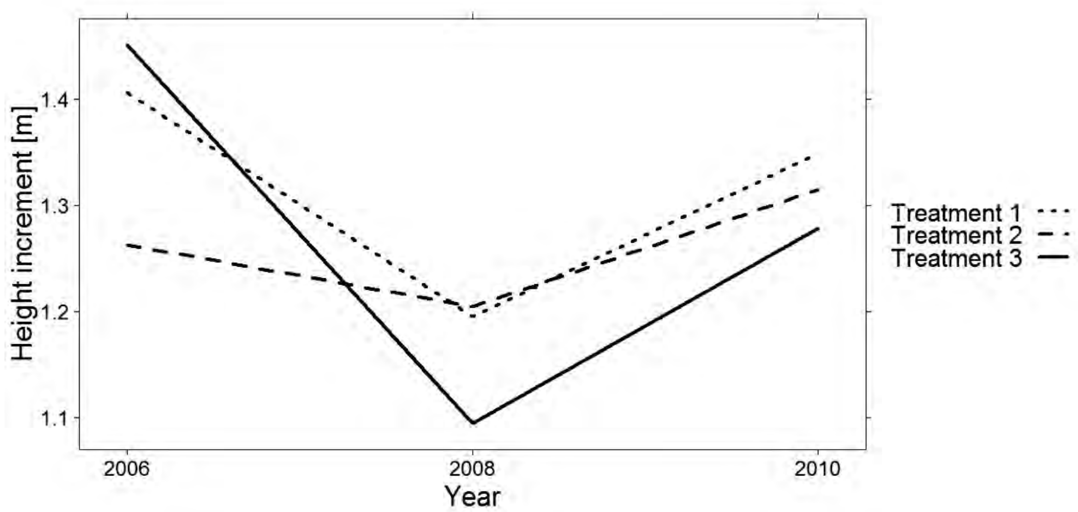

Fig. 4.29 Mean 2-year tree height increment in the Crane Lake. Lines represent treatments: 1- removal of every third row, 2- removal of every third row and crown thinning, 3- no thinning (control plot).

According to the ANOVA results (Table 4.8), there was significant difference between average total tree height increment for different treatments only in 2006. However, due to relevant interaction between blocks and treatments (Fig. 9.5) the Tukey multiple comparison test was not performed.

Table 4.8
The analysis of variance results for tree height increment in the Crane Lake.

Year	Source	Degrees of freedom	Sum of squares	MSE (mean square error)	F value	Pr (>F)	Bartlett test (p value)
	Treatments	2	0.3012	0.1506	6.3614	**0.00414***	
2006	Block	3	0.1505	0.0502	2.1195	0.11383	0.5921
	Residuals	38	0.8996	0.0237			
	Treatments	2	0.1286	0.0643	2.9770	0.06294	
2008	Block	3	0.0813	0.0271	1.2546	0.30364	0.103
	Residuals	3	0.8207	0.0216			
	Treatments	2	0.0383	0.0192	0.7845	0.4636	
2010	Block	3	0.1107	0.0369	1.5110	0.2272	0.6574
	Residuals	38	0.9281	0.0244			

*significant on the significance level α=0.05

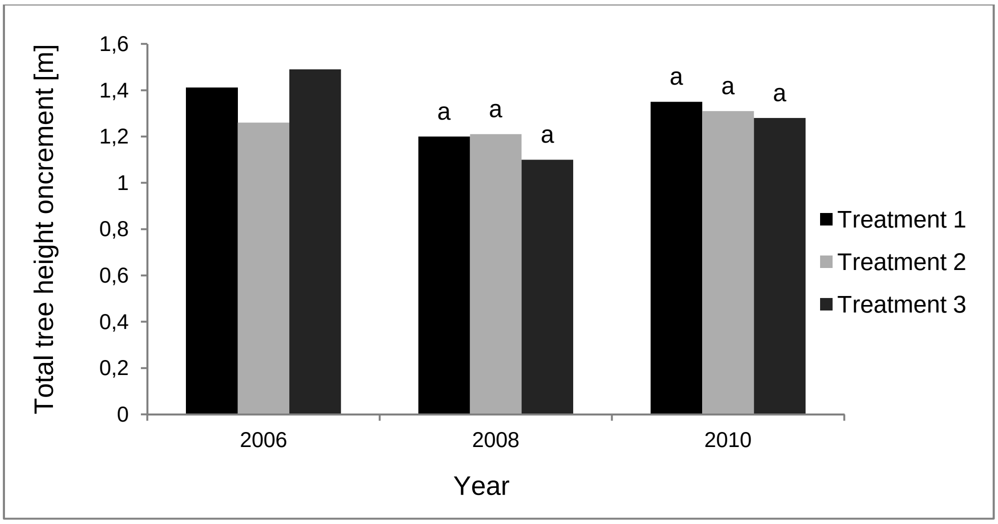

Fig. 4.30 Mean 2-year tree height increment in the Crane Lake for different years and treatments: 1- removal of every third row, 2- removal of every third row and crown thinning, 3- no thinning (control plot). Different letters above bars indicate significant differences between means according to the Tukey test. Lack of letters above bars indicates significant blocks-treatments interaction.

4.4.3 Middle Branch East Thinning Trial

Average tree height and increased with increasing stand density and was constant across all treatments (Fig. 4.31). Height increment was also the largest for the control plot, but generally not dependent on stand density (Fig. 4.32).

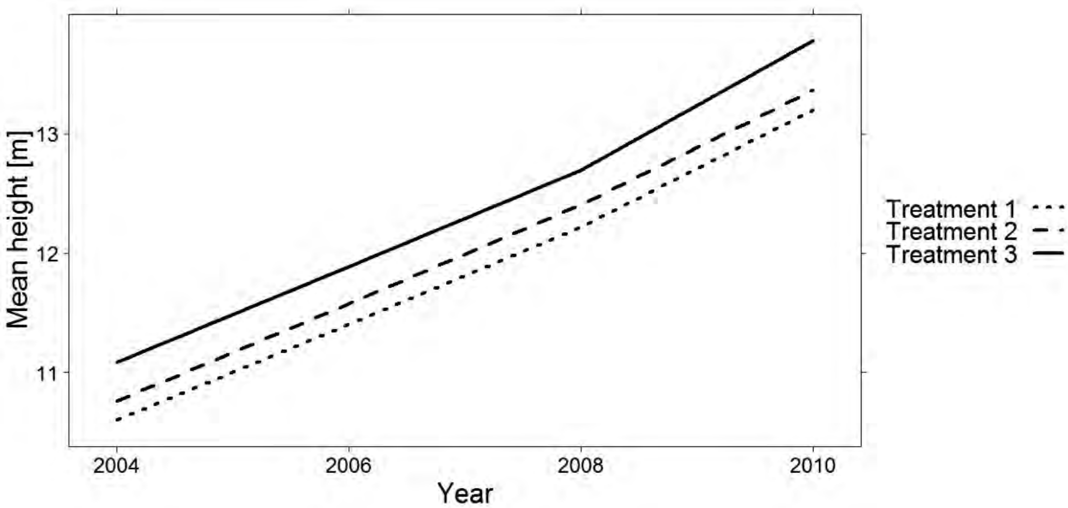

Fig. 4.31 Mean tree height in the Middle Branch East. Lines represent treatments: 1- removal of every third row plus one in three dominant or codominant trees, 2- removal of every third row plus one in five dominant or codominant trees, 3- no thinning (control plot).

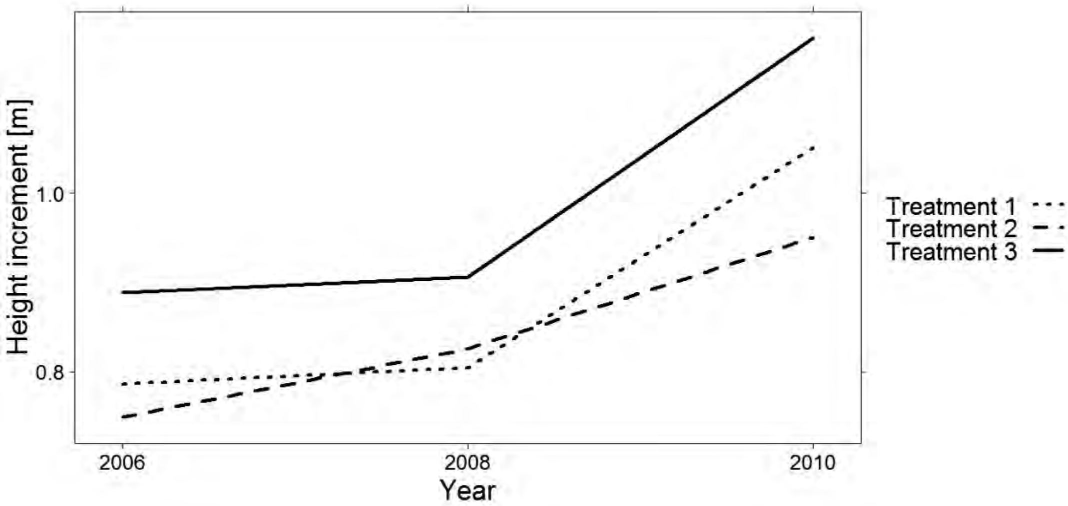

Fig. 4.32 Mean 2-year tree height increment in the Middle Branch East. Lines represent treatments: 1- removal of every third row plus one in three dominant or codominant trees, 2- removal of every third row plus one in five dominant or codominant trees, 3- no thinning (control plot).

According to the analysis of variance results (Table 4.9), there was no relevant effect of thinning type on total tree height. Height increment was the largest for the control plot, though differences between treatments were very small (Fig. 4.32, Fig. 4.33).

Table 4.9
The analysis of variance results for tree height increment in the Middle Branch East.

Year	Source	Degrees of freedom	Sum of squares	MSE (mean square error)	F value	Pr (>F)	Bartlett test (p value)
2006	Treatments	2	0.12803	0.064016	1.5405	0.2319	7.966e-05
	Block	2	0.09217	0.046086	1.1090	0.3439	
	Residuals	28	1.16357	0.041556			
2008	Treatments	2	0.07537	0.037687	0.8229	0.4495	0.001794
	Block	2	0.15212	0.076061	1.6608	0.2082	
	Residuals	28	1.28234	0.045798			
2010	Treatments	2	0.32892	0.16446	1.5838	0.22303	0.00285
	Block	2	0.52964	0.26482	2.5503	0.09605	
	Residuals	28	2.90745	0.10384			

*significant on the significance level α=0.05

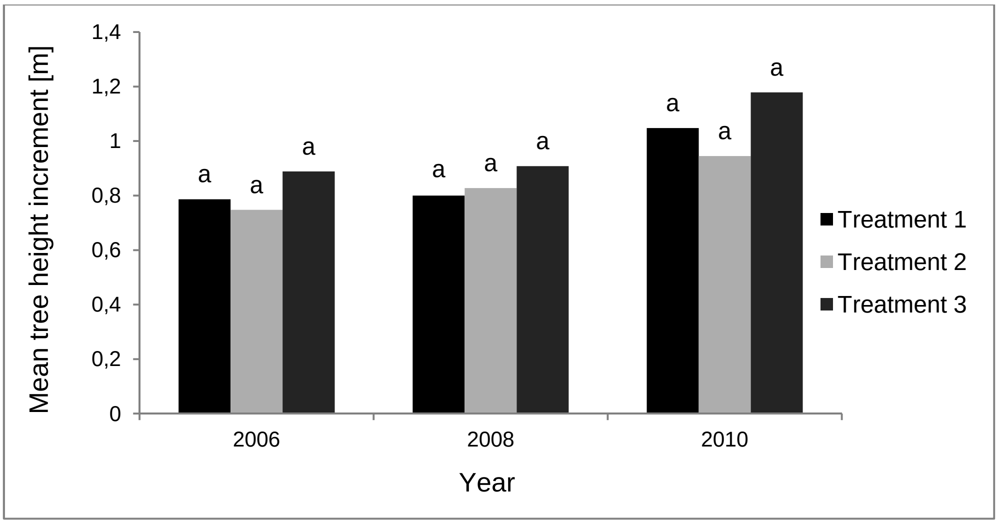

Fig. 4.33 Mean 2-year height increment in the Middle Branch East for different years and treatments: 1- removal of every third row plus one in three dominant or codominant trees, 2- removal of every third row plus one in five dominant or codominant trees, 3- no thinning (control plot). Different letters above bars indicate significant differences between means according to the Tukey test. Lack of letters above bars indicates significant blocks- treatments interaction.

4.5 Average live crown length

In general, live crown length increased with increasing thinning intensity. The exception was the Atlantic Mine trial in which the longest crowns occurred in plots, where thinning from below was applied. This was probably because smaller trees with shorter crowns were removed, which increased average crown length. Due to common blocks- treatments interaction, differences between mean increments for alternative treatments could not be tested for all years. However, for years when Tukey test could be performed, no significant difference was detected between thinnings, except control plot where significantly smaller increments occurred compared to other treatments. Nevertheless, crown length increments tended to be the largest in the heaviest treatments and the smallest in control plots.

4.5.1 Atlantic Mine Thinning Trial

The shortest tree crown and annual crown increments were observed for the control plot, while the longest for the thinning from below (Fig. 4.34). The increment was the smallest in the control plot and the most rapid for the heaviest thinning, treatment 2 (Fig. 4.35).

The analysis of variance confirmed that the crown length response to different thinning treatments differs significantly among them (Table 4.10). Mean live crown length increment between in 2008 was significantly higher for treatment 1 and 3 compared to the control plot (Fig. 4.36). The Tukey multiple comparison test could not be performed for 2010 increment due to important blocks- treatments interaction (Fig. 9.2).

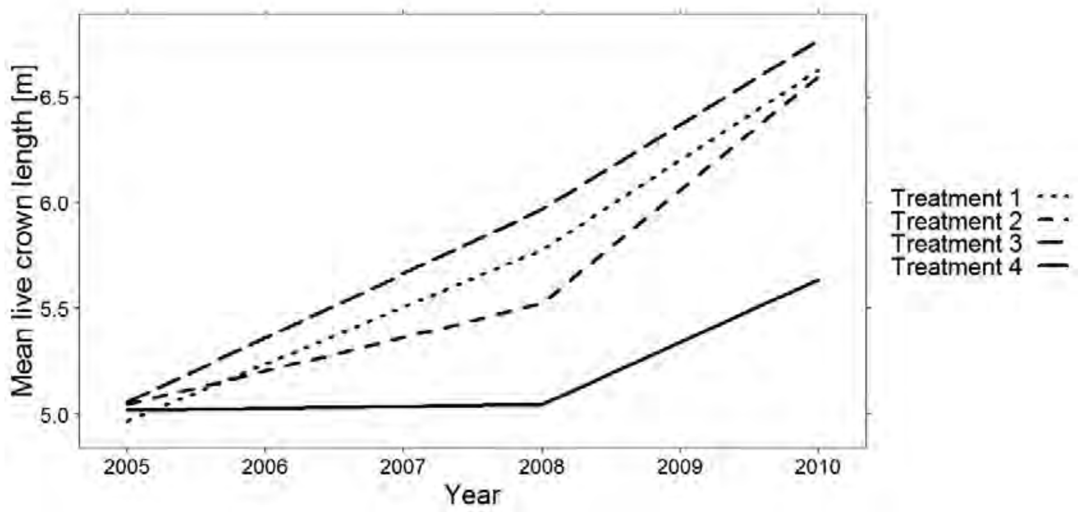

Fig. 4.34 Mean live crown length in the Atlantic Mine. Lines represent treatments: 1- removal of every fifth row plus crown thinning, 2- removal of every third row plus crown thinning, 3- removal of every third row plus thinning from below, 4- no thinning (control plot)

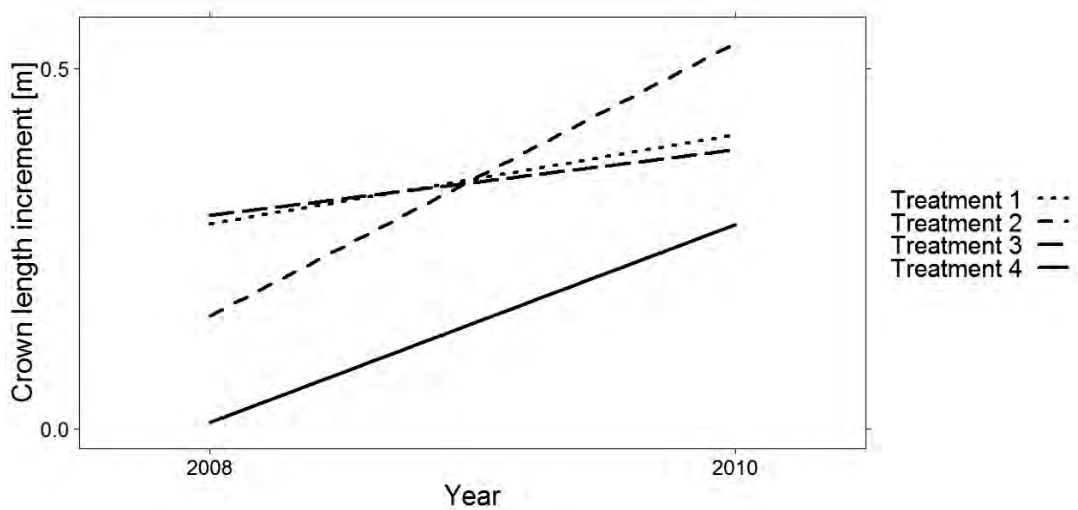

Fig. 4.35 Mean 1-year live crown length increment in the Atlantic Mine. Lines represent treatments: 1- removal of every fifth row plus crown thinning, 2- removal of every third row plus crown thinning, 3- removal of every third row plus thinning from below, 4- no thinning (control plot).

Table 4.10

The analysis of variance results for live crown length increment in the Atlantic Mine.

Year	Source	Degrees of freedom	Sum of squares	MSE (mean square error)	F value	Pr (>F)	Bartlett test (p value)
	Treatments	3	4.1514	1.3838	17.2064	**1.90E-06***	
2008	Block	2	1.4157	0.7079	8.8017	0.00114	0.0197
	Residuals	27	2.1714	0.0804			
	Treatments	3	1.0593	0.3531	6.0121	**0.002831***	
2010	Block	2	0.5483	0.2741	4.6677	0.018153	0.1097
	Residuals	27	1.5857	0.0587			

*significant on the significance level α=0.05

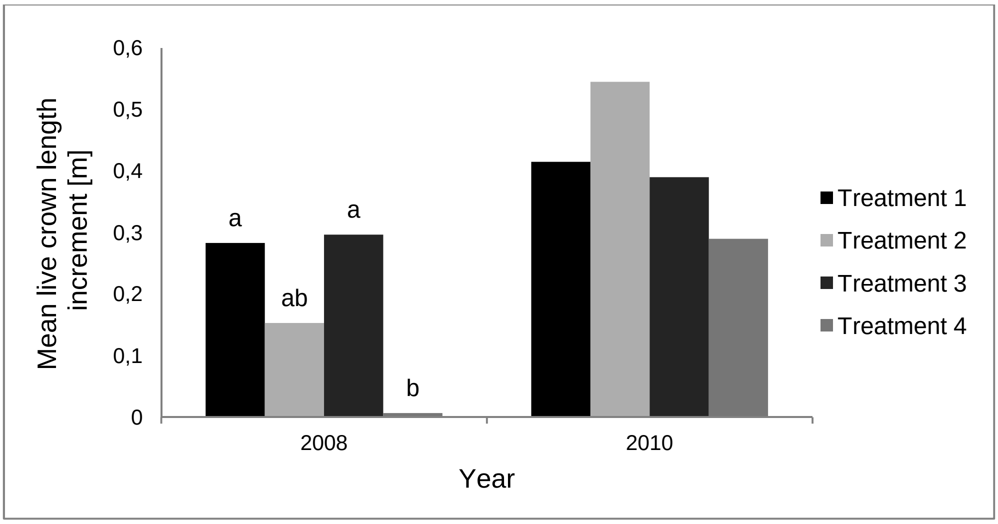

Fig. 4.36 Mean 1-year live crown length increment in the Atlantic Mine for different years and treatments: 1- removal of every fifth row plus crown thinning, 2- removal of every third row plus crown thinning, 3- removal of every third row plus thinning from below, 4- no thinning (control plot). Different letters above bars indicate significant differences between means according to the Tukey test. Lack of letters above bars indicates significant blocks- treatments interaction.

4.5.2 Crane Lake Thinning Trial

Live crown lengths did not differ substantially between treatments in the beginning of the measurement period (Fig. 4.37). After 2006 differences started to increase. For this period average length of live crown was the shortest in the control plot and the longest in plots where simple row thinning was applied, treatment 1. The smallest live crown increments were noticed in the control plots, whereas the largest was mainly observed for the row harvest with thinning from above in residual rows (Fig. 4.38).

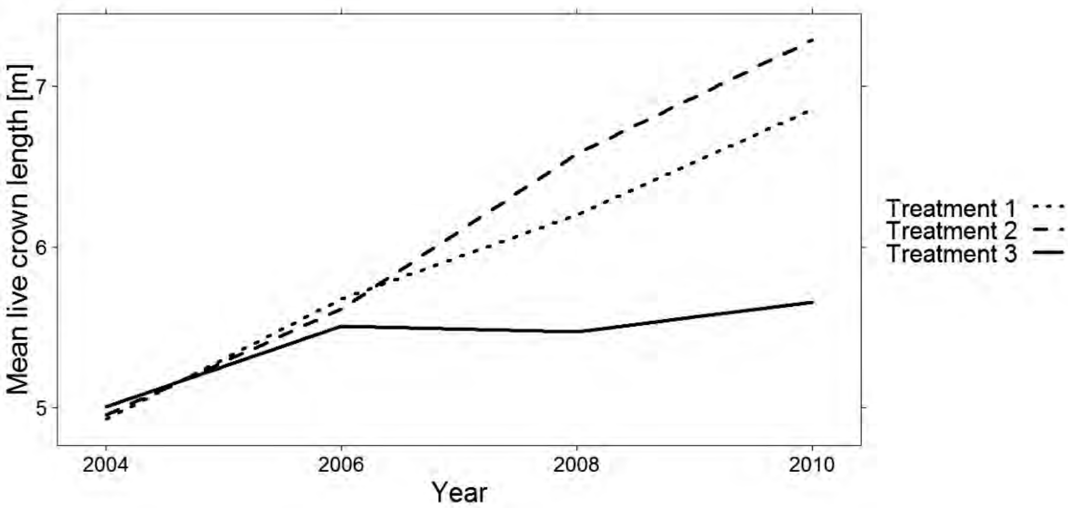

Fig. 4.37 Mean live crown length in the Crane Lake. Lines represent treatments: 1- removal of every third row, 2- removal of every third row and crown thinning, 3- no thinning (control plot).

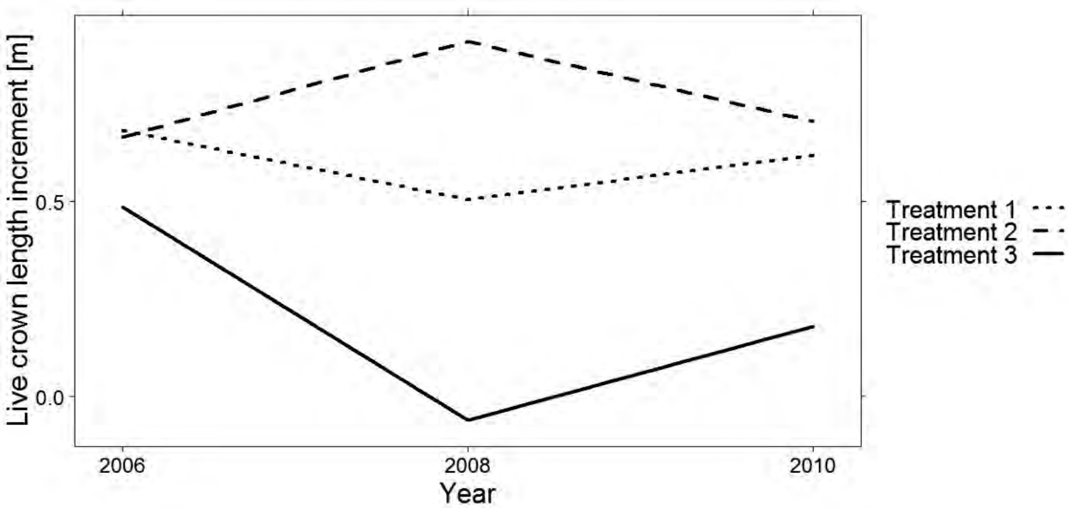

Fig. 4.38 Mean 2-year live crown length increment in the Crane Lake. Lines represent treatments: 1- removal of every third row, 2- removal of every third row and crown thinning, 3- no thinning (control plot).

The ANOVA confirmed significant differences in mean live crown length change due to different treatments for all years of measurements. The Tukey test showed substantial difference between control plot and plots where thinnings were applied for the year 2008 (Fig. 4.39). The multiple comparison test was not performed for years 2006 and 2010 due to significant interaction between blocks and treatments (Fig. 9.2).

Table 4.11
The analysis of variance results for live crown length increment in the Crane Lake.

Year	Source	Degrees of freedom	Sum of squares	MSE (mean square error)	F value	Pr (>F)	Bartlett test (p value)
	Treatments	2	0.3749	0.1875	4.6100	**0.01612***	
2006	Block	3	1.1249	0.3750	9.2207	0.00010	0.0844
	Residuals	38	1.5453	0.0407			
	Treatments	2	7.2377	3.6189	54.0520	**7.71e-12***	
2008	Block	3	2.2604	0.7535	11.2540	2.01e-05	0.5029
	Residuals	38	2.5441	0.0670			
	Treatments	2	2.4168	1.2084	13.8426	**3.05e-05***	
2010	Block	3	0.2561	0.0854	0.9779	0.4133	0.9469
	Residuals	38	3.3172	0.0873			

*significant on the significance level α=0.05

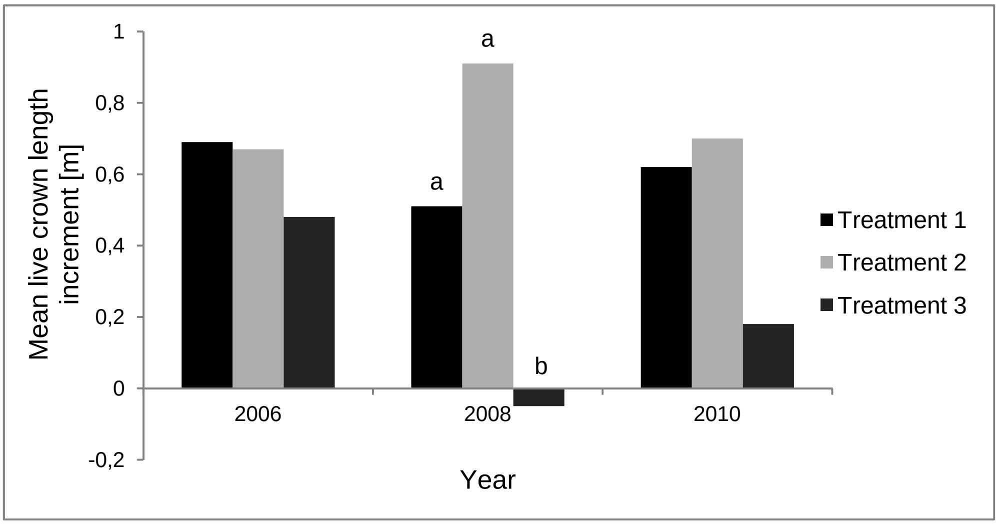

Fig. 4.39 Mean 2-year live crown length increment in the Crane Lake for different years and treatments: 1- removal of every third row, 2- removal of every third row and crown thinning, 3- no thinning (control plot). Different letters above bars indicate significant differences between means according to the Tukey test. Lack of letters above bars indicates significant blocks-treatments interaction.

4.5.3 Middle Branch East Thinning Trial

Average live crown length decreased with increasing thinning intensity, but did not differ substantially between treatments 1 and 2 (Fig. 4.40). Crown length and its increment (Fig. 4.41, Fig. 4.42) were the smallest in the control plot.

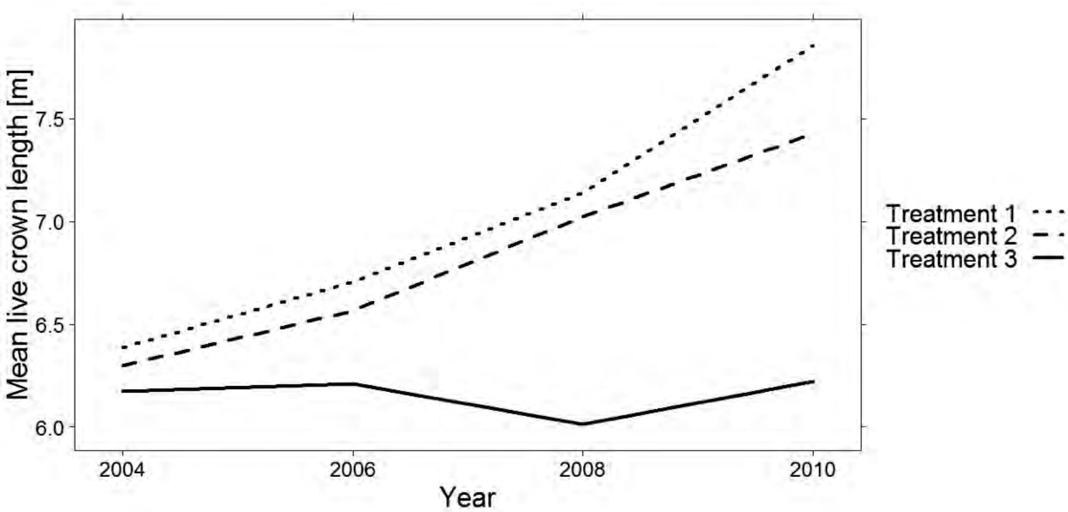

Fig. 4.40 Mean live crown length in the Middle Branch East. Lines represent treatments: 1- removal of every third row plus one in three dominant or codominant trees, 2- removal of every third row plus one in five dominant or codominant trees, 3- no thinning (control plot).

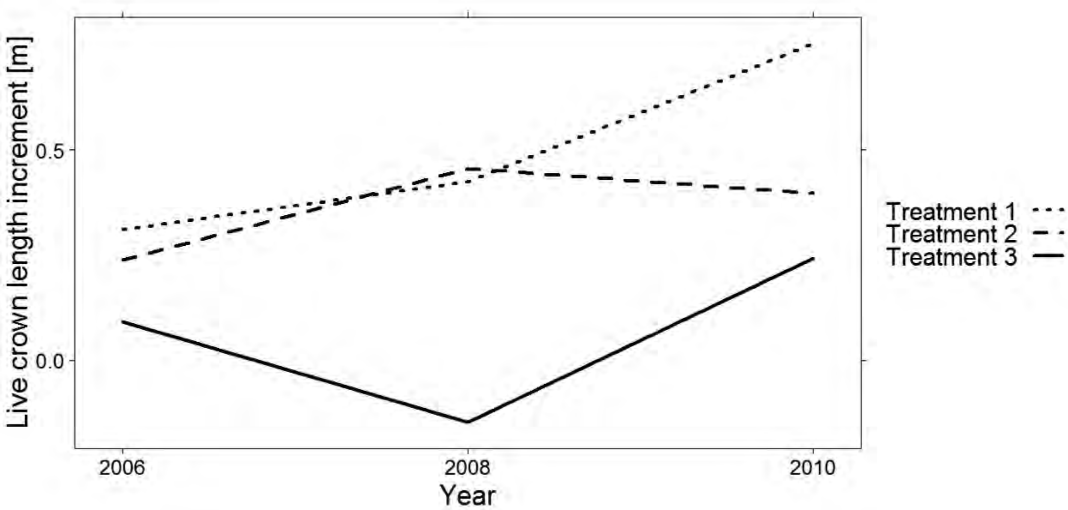

Fig. 4.41 Mean 2-year live crown length increment in the Middle Branch East. Lines represent treatments: 1- removal of every third row plus one in three dominant or codominant trees, 2- removal of every third row plus one in five dominant or codominant trees, 3- no thinning (control plot).

Despite significant differences between treatment effects on the live crown length increment (Table 4.12), substantial interactions between treatments and blocks can be observed (Fig. 9.2), thus multiple comparison test could not be performed (Fig. 4.42).

Table 4.12
The analysis of variance results for live crown length increment in the Middle Branch East.

Year	Source	Degrees of freedom	Sum of squares	MSE (mean square error)	F value	Pr (>F)	Bartlett test (p value)
	Treatments	2	0.31029	0.15515	5.7927	**0.007847***	
2006	Block	2	0.00718	0.00359	0.1341	0.875090	0.8022
	Residuals	28	0.74992	0.02678			
	Treatments	2	2.68489	1.34244	23.1291	**1.174e-06***	
2008	Block	2	0.22011	0.11005	1.8961	0.1689	0.3193
	Residuals	28	1.62516	0.05804			
	Treatments	2	1.62249	0.81125	8.7278	**0.001132***	
2010	Block	2	0.01928	0.00964	0.1037	0.901810	0.3509
	Residuals	28	2.60259	0.09295			

*significant on the significance level α=0.05

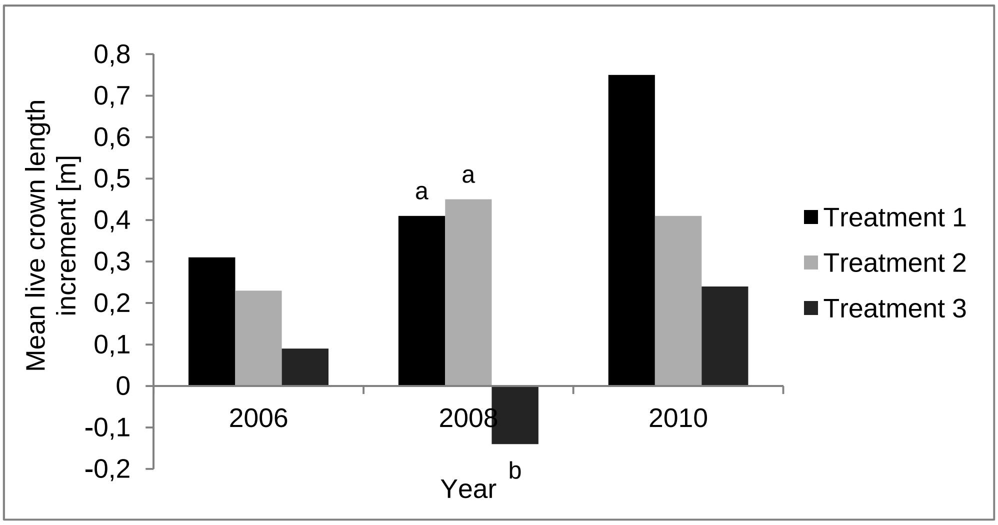

Fig. 4.42 Mean 2-year live crown length increment in the Middle Branch East for different years and treatments: 1- removal of every third row plus one in three dominant or codominant trees, 2- removal of every third row plus one in five dominant or codominant trees, 3- no thinning (control plot). The Tukey test not performed due to significant blocks- treatments interaction.

4.6 Ratio of live crown length to tree height

Crown ratio was the smallest and was decreasing in time in control plots. For remaining treatments it was higher and rather stable or increasing in time.

4.6.1 Atlantic Mine Thinning Trial

Ratio of the length of live crown to tree height in the control plot decreased substantially between 2005 and 2008, and then slightly recovered (Fig. 4.43). A comparable trend (decreasing and then increasing), but higher ratios were the result of treatment 2. Among remaining treatments, row harvest plus thinning from below (treatment 3) obtained the largest crown-height ratio, which was increasing in time. Similar tendency, but lower values, was observed for row thinning (treatment 1).

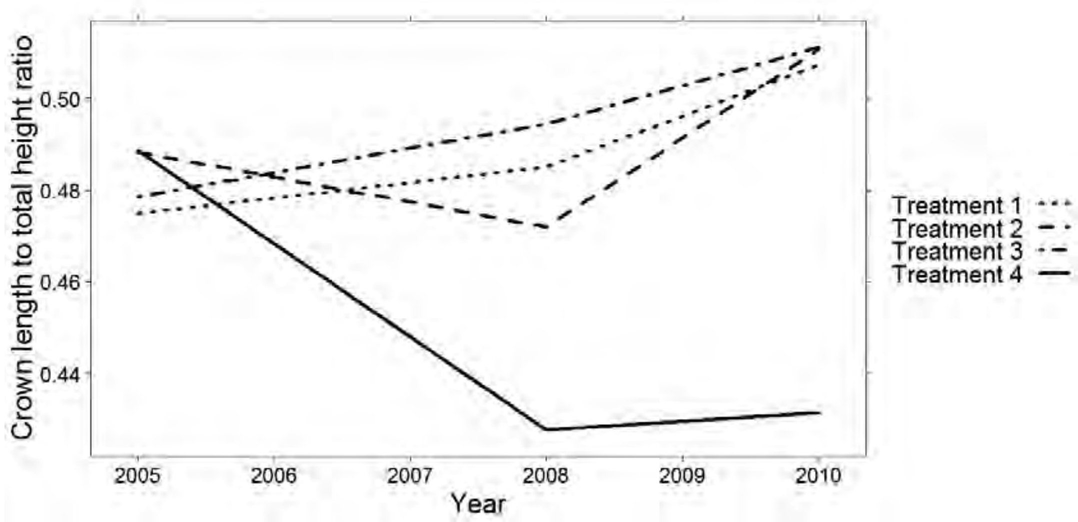

Fig. 4.43 Ratio of live crown length to height in the Atlantic Mine. Treatments numbers refer to: 1- removal of every fifth row plus crown thinning, 2- removal of every third row plus crown thinning, 3- removal of every third row plus thinning from below, 4- no thinning (control plot).

4.6.2 Crane Lake Thinning Trial

Control plot maintained decreasing trend and the smallest values of crown ratio in time (Fig. 4.44). In the case of row thinning (treatment 1), the ratio was rather stable over the measurement period. There was an increase in crown length to tree height ratio for the most intensive thinning- treatment 2.

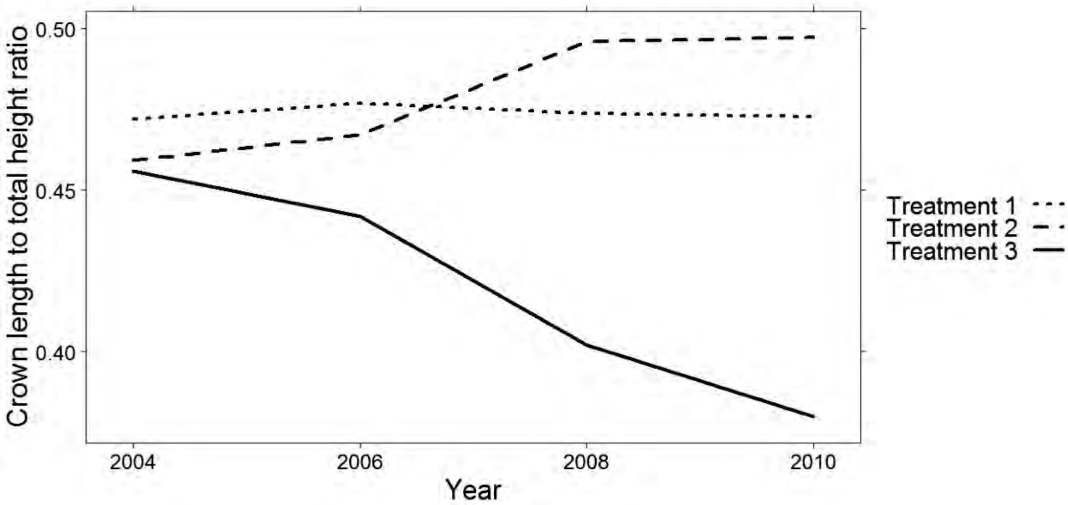

Fig. 4.44 Ratio of live crown length to height in the Crane Lake. Treatments numbers refer to: 1- removal of every third row, 2- removal of every third row and crown thinning, 3- no thinning (control plot).

4.6.3 Middle Branch East Thinning Trial

Crown length to tree height ratio decreased the most substantially in time for the control plot (Fig. 4.45). It maintained declining trend in the case of treatment 2 as well, however it was rather slight decrease. The same tendency was observed also for the most intensive thinning (treatment 1) until the year 2008, when the ratio began to increase.

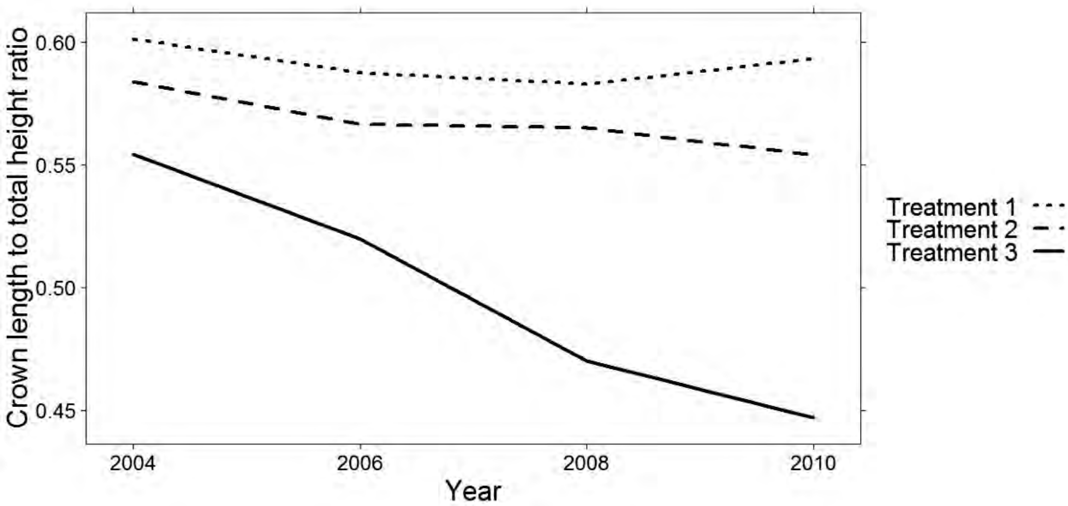

Fig. 4.45 Ratio of live crown length to height in the Middle Branch East. Treatment numbers refer to: 1- removal of every third row plus one in three dominant or codominant trees, 2- removal of every third row plus one in five dominant or codominant trees, 3- no thinning (control plot).

4.7 Stand volume and volume increment

There was a common trend of increasing stand volume with decreasing thinning intensity in all trials, typical for the chainsaw effect. The relative decrease was in correspondence to the reduction in basal area. Volume increment decreased with decreasing standing volume. For available data, there was a significant difference between control plot and other treatments, but not among them, in their effect on volume increment. Ratio of volume increment to standing volume decreased with increasing thinning intensity. However, significant differences did not occur between plots where thinnings were applied, but only in their comparison with control plots.

4.7.1 Atlantic Mine Thinning Trial

After the harvest in spring 2006, volume decreased by 45% for treatment 1, 48% for treatment 2 and 43% for the treatment 3 (Fig. 4.46).

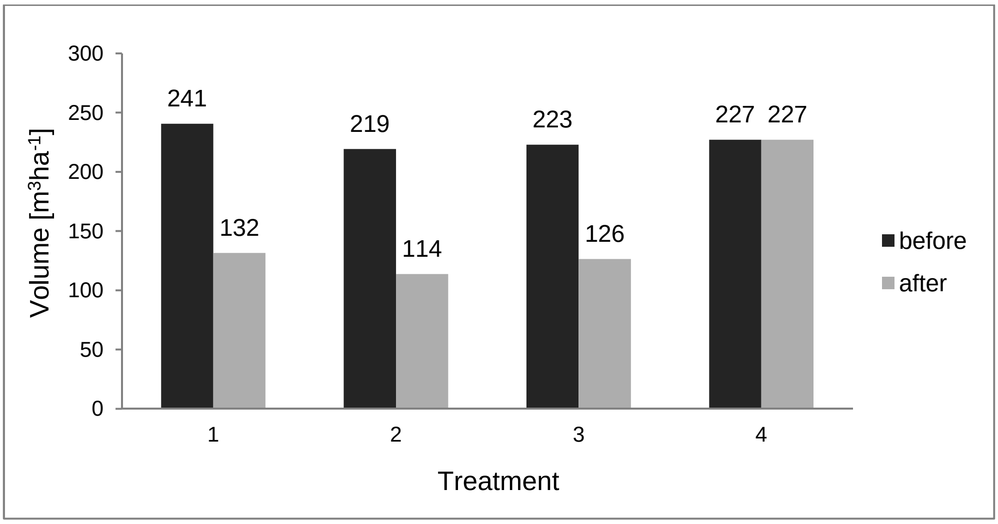

Fig. 4.46 Stand volume in the Atlantic Mine before and after the harvest in 2006 for different thinning treatments: 1- removal of every fifth row plus crown thinning, 2- removal of every third row plus crown thinning, 3- removal of every third row plus thinning from below, 4- no thinning (control plot).

According to Fig. 4.47, average volume in control plot was approximately twice as large as in case of remaining treatments, which gave similar results. Analogous trends occurred for 1-year volume increment (Fig. 4.48). Reversed situation was observed for ratio of volume increment to standing volume (Fig. 4.49). The highest slope of this attribute occurred in the heaviest thinning, while it was relatively stable in the control plot, however spread between treatments increased in time.

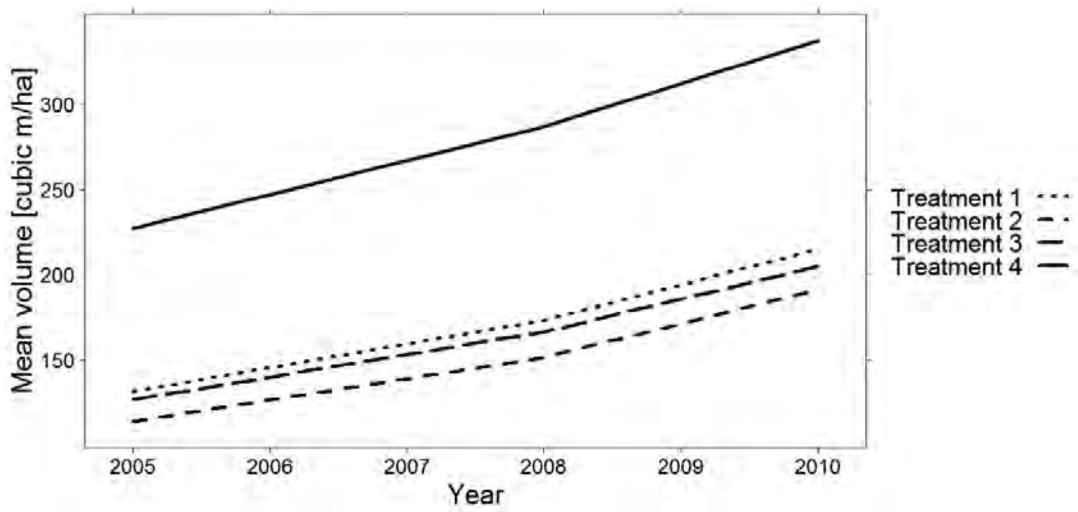

Fig. 4.47 Mean volume in the Atlantic Mine. Lines represent treatments: 1- removal of every fifth row plus crown thinning, 2- removal of every third row plus crown thinning, 3- removal of every third row plus thinning from below, 4- no thinning (control plot).

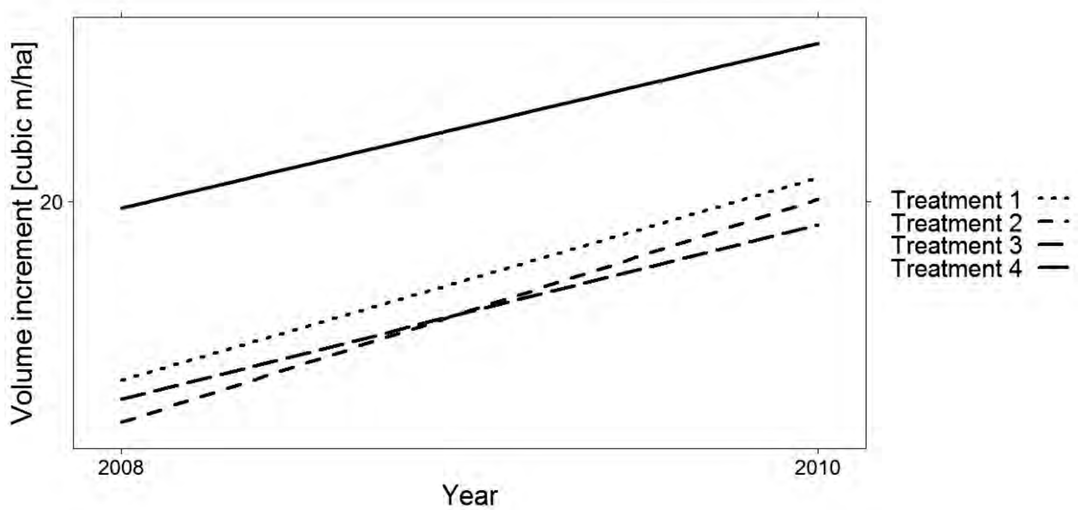

Fig. 4.48 Mean 1-year volume increment in the Atlantic Mine. Lines represent treatments: 1- removal of every fifth row plus crown thinning, 2- removal of every third row plus crown thinning, 3- removal of every third row plus thinning from below, 4- no thinning (control plot).

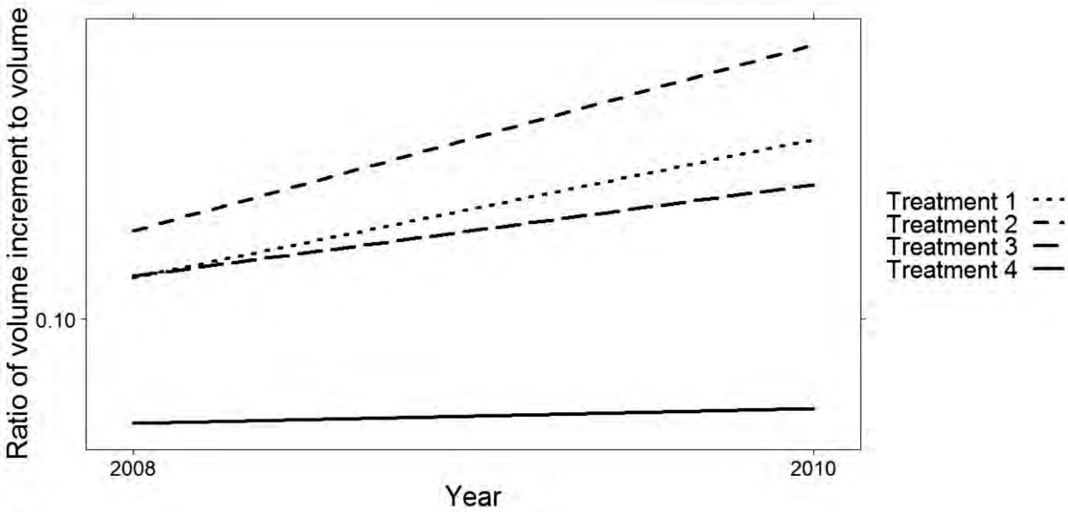

Fig. 4.49 Ratio of 1-year volume increment to standing volume in the Atlantic Mine. Lines represent treatments: 1- removal of every fifth row plus crown thinning, 2- removal of every third row plus crown thinning, 3- removal of every third row plus thinning from below, 4- no thinning (control plot).

The ANOVA table (Table 4.13) contains results confirming significant differences between treatments in terms of their effect on volume change for both, 2008 and 2010, years. Due to significant interaction between blocks and treatments in 2010 (Fig. 9.3), the Tukey test was performed only for the year 2008 (Fig. 4.50).

Table 4.13
The analysis of variance results for mean 1-year volume increment in the Atlantic Mine.

Year	Source	Degrees of freedom	Sum of squares	MSE (mean square error)	F value	Pr (>F)	Bartlett test (p value)
2008	Treatments	3	2574.81	858.27	15.763	**4.03E-06***	0.0687
	Block	2	60.11	30.05	0.552	0.5822	
	Residuals	27	1470.11	54.45			
2010	Treatments	3	759.63	253.21	8.6314	**0.000352***	0.7631
	Block	2	338.73	169.37	5.7734	0.008177	
	Residuals	27	792.07	29.34			

*significant on the significance level α=0.05

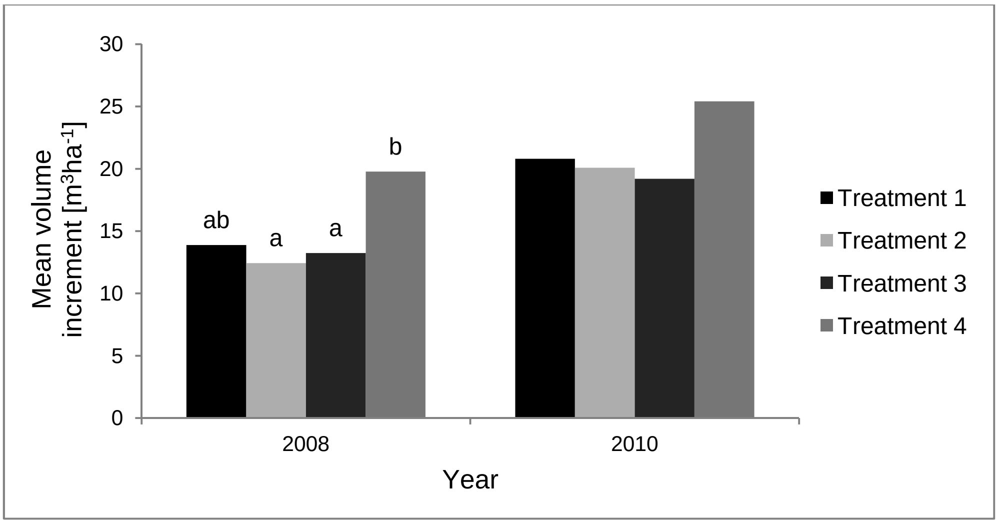

Fig. 4.50 Mean 1-year volume increment in the Atlantic Mine for different years and treatments: 1- removal of every fifth row plus crown thinning, 2- removal of every third row plus crown thinning, 3- removal of every third row plus thinning from below, 4- no thinning (control plot). Different letters above bars indicate significant differences between means according to the Tukey test. Lack of letters above bars indicates significant blocks- treatments interaction.

The Analysis of variance performed for ratio of 1-year volume increment to standing volume gave comparable results (Table 4.14). Though the Tukey test was performed only for 2010 (Fig. 4.51) due to significant interaction between blocks and treatments in 2008 (Fig. 9.4).

Table 4.14
The analysis of variance results for ratio of 1- year volume increment to standing volume in the Atlantic Mine.

Year	Source	Degrees of freedom	Sum of squares	MSE (mean square error)	F value	Pr (>F)	Bartlett test (p value)
2006	Treatments	3	0.002185	0.0007285	5.6911	**0.003737***	0.183
	Block	2	0.001564	0.0007820	6.1095	0.006475	
	Residuals	27	0.003456	0.0001280			
2008	Treatments	3	0.008312	0.0027706	17.0750	**2.034e-06***	0.338
	Block	2	0.000879	0.0004396	2.7094	0.08466	
	Residuals	27	0.004381	0.0001622			

*significant on the significance level α=0.05

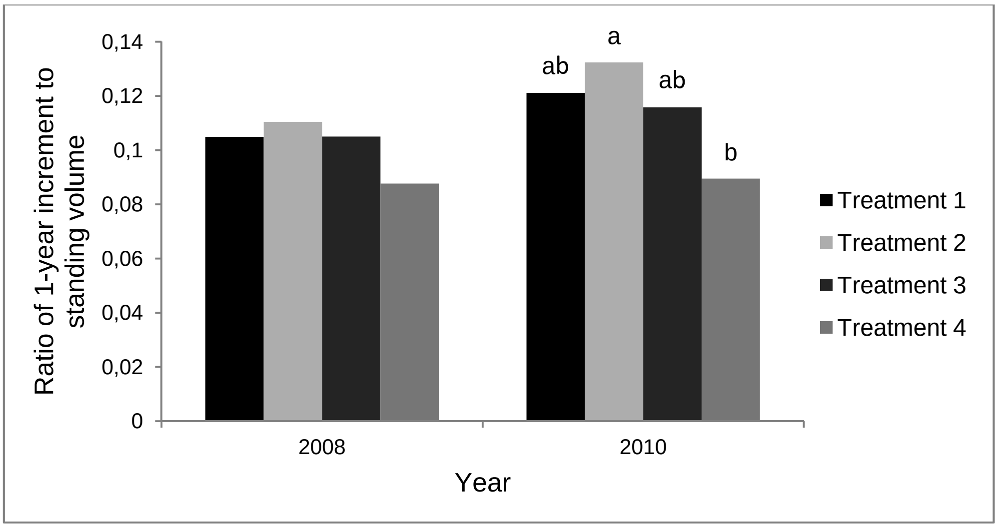

Fig. 4.51 Mean ratio of 1-year volume increment to standing volume the Atlantic Mine for different years and treatments: 1- removal of every fifth row plus crown thinning, 2- removal of every third row plus crown thinning, 3- removal of every third row plus thinning from below, 4- no thinning (control plot). Different letters above bars indicate significant differences between means according to the Tukey test. Lack of letters above bars indicates significant blocks-treatments interaction.

4.7.2 Crane Lake thinning trial

After the thinnings in 2004, average volume decreased by 30% for treatment 1 and 32% for treatment 2 (Fig. 4.52).

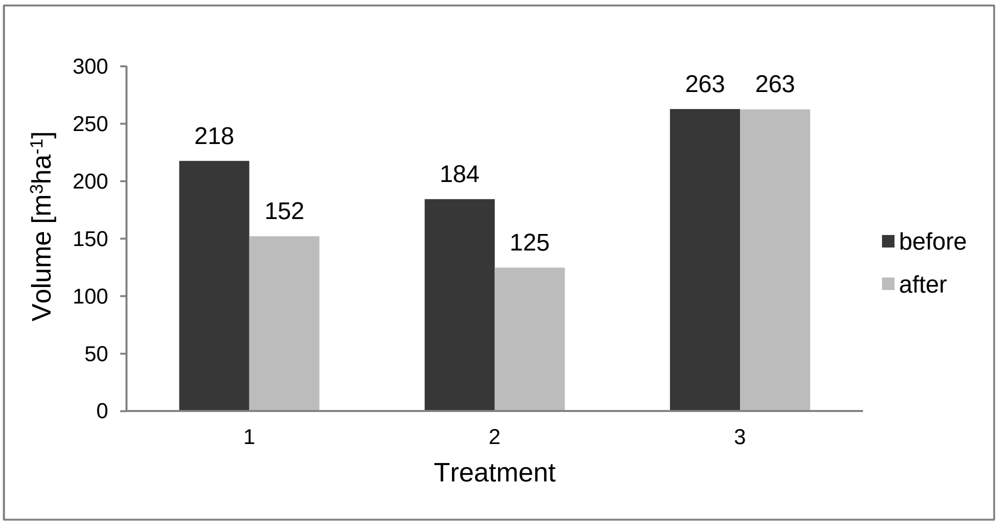

Fig. 4.52 Stand volume in the Crane Lake before and after the thinning in 2004 for different thinning treatments: 1- removal of every third row, 2- removal of every third row and crown thinning, 3- no thinning (control plot).

Average stand volume and 2-year volume increment increased with decreasing thinning intensity (Fig. 4.53, Fig. 4.54), however there was a decline in increment between 2006 and 2008. Decrease in ratio of 2-year volume increment to standing volume also occurred till 2008, after which remained rather stable.

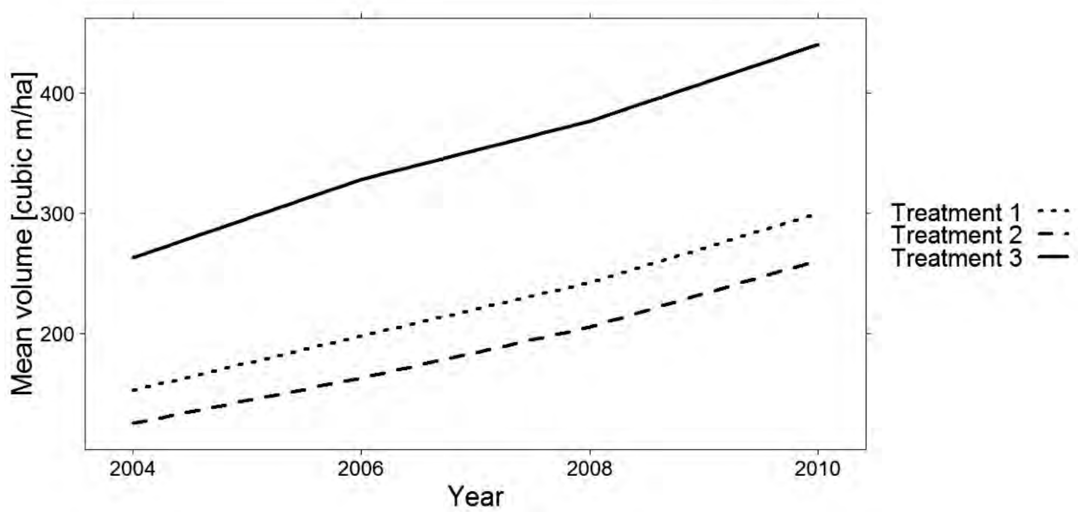

Fig. 4.53 Mean volume in the Crane Lake. Lines represent treatments: 1- removal of every third row, 2- removal of every third row and crown thinning, 3- no thinning (control plot).

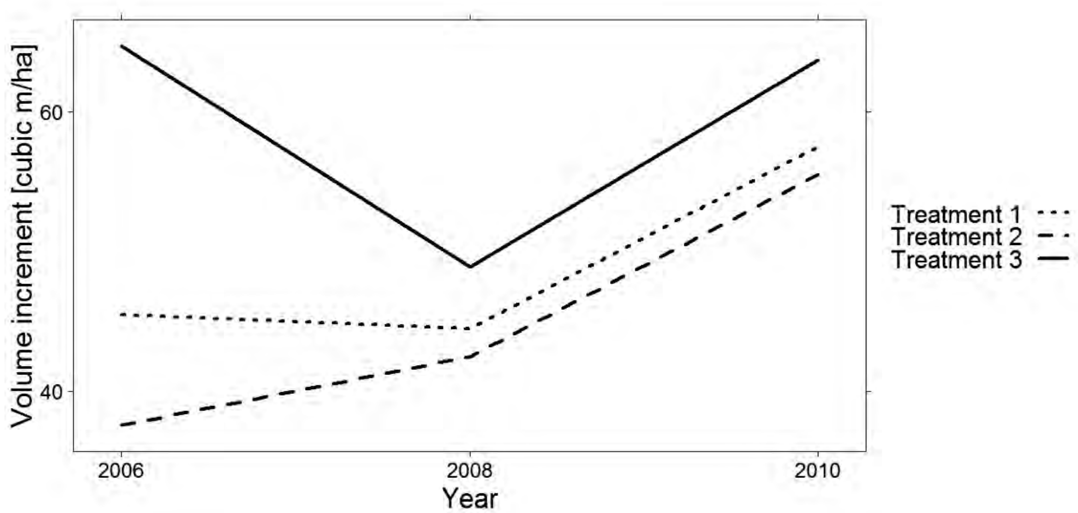

Fig. 4.54 Mean 2-year volume increment in the Crane Lake. Lines represent treatments: 1- removal of every third row, 2- removal of every third row and crown thinning, 3- no thinning (control plot).

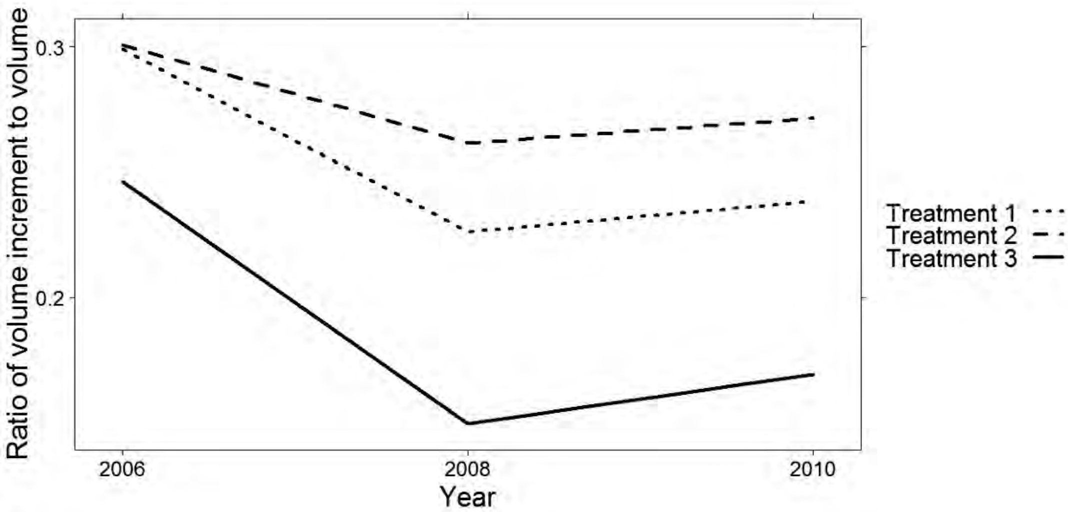

Fig. 4.55 Ratio of 2-year volume increment to standing volume in the Crane Lake. Lines represent treatments: 1- removal of every third row, 2- removal of every third row and crown thinning, 3- no thinning (control plot).

Table 4.15 presents the results of the analysis of variance for mean 2-year volume increment. There was significant difference between treatments for all years when data were available. Due to relevant interactions between blocks and treatments in years 2008 and 2010 (Fig. 9.3), the Tukey test was performed only for the year 2006 and confirmed substantial differences between the control plot and thinned plots (Fig. 4.56).

Table 4.15

The analysis of variance results for mean 2-year volume increment in the Crane Lake.

Year	Source	Degrees of freedom	Sum of squares	MSE (mean square error)	F value	Pr (>F)	Bartlett test (p value)
2006	Treatments	2	6058.60	3029.32	111.118	**<2e-16***	0.9199
	Block	3	99.80	33.25	1.2198	0.3158	
	Residuals	38	1036.00	27.26			
2008	Treatments	2	301.13	150.564	3.7825	**0.03176***	0.02572
	Block	3	159.07	53.024	1.3320	0.27827	
	Residuals	38	1512.63	39.806			
2010	Treatments	2	574.83	287.415	11.4280	**0.000130***	0.7992
	Block	3	254.75	84.918	3.3765	0.028064	
	Residuals	38	9555.70	25.150			

*significant on the significance level α=0.05

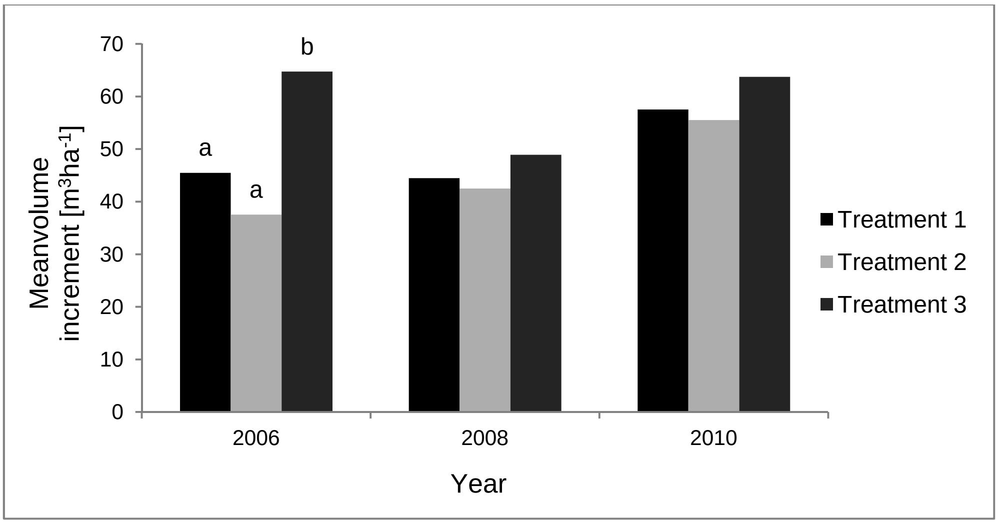

Fig. 4.56 Mean 2-year volume increment in the Crane Lake for different years and treatments: 1- removal of every third row, 2- removal of every third row and crown thinning, 3- no thinning (control plot). Different letters above bars indicate significant differences between means according to the Tukey test. Lack of letters above bars indicates significant blocks- treatments interaction.

The analysis of variance for 2-year volume increment to standing volume ratio revealed significant differences between treatments for all years (Table 4.16). The Tukey test showed significant difference between control plot versus both thinning treatments (Fig 4.55).)

Table 4.16
The analysis of variance results for ratio of 2-year volume increment to standing volume in the Crane Lake.

Year	Source	Degrees of freedom	Sum of squares	MSE (mean square error)	F value	P (>F)	Bartlett test (p value)
	Treatments	2	0.029278	0.0146388	29.0604	**2.2e-08***	
2006	Block	3	0.000399	0.0001329		0.851	0.09663
	Residuals	38	0.019142	0.0005037	0.2639		
	Treatments	2	0.104148	0.052074	101.422	**5.793e-16***	
2008	Block	3	0.003797	0.001266	2.465	0.07704	0.5058
	Residuals	38	0.019511	0.000513			
	Treatments	2	0.082518	0.041259	133.615	**<2e-16***	
2010	Block	3	0.000902	0.000301		0.415	0.05204
	Residuals	38	0.011734	0.000309	0.9742		

*significant on the significance level α=0.05

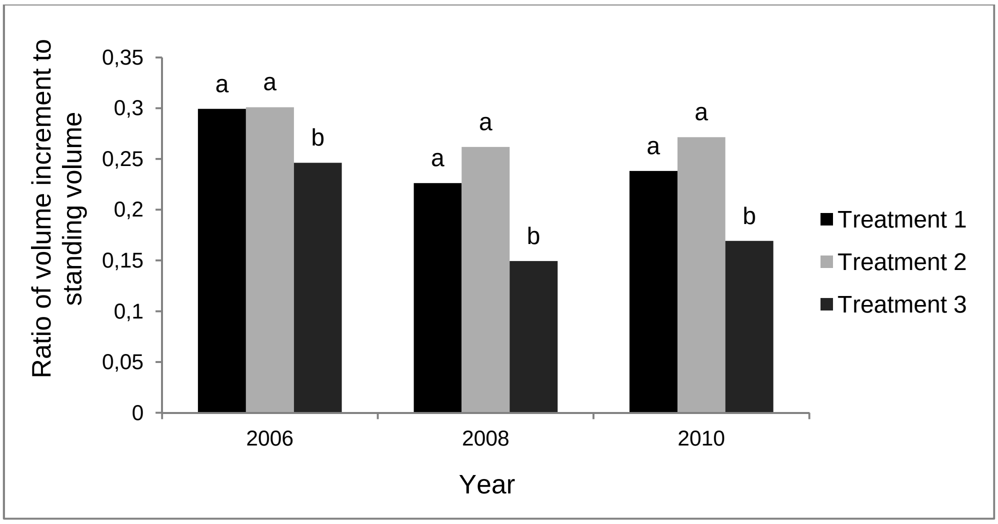

Fig. 4.57 Mean ratio of 2-year volume increment to standing volume in the Crane Lake for different years and treatments: 1- removal of every third row, 2- removal of every third row and crown thinning, 3- no thinning (control plot). Different letters above bars indicate significant differences between means according to the Tukey test. Lack of letters above bars indicates significant blocks- treatments interaction.

4.7.3 Middle Branch East Thinning Trial

After the harvest in 2004, average volume per hectare decreased by 44% due to treatment 1 and 42% for treatment 2 (Fig. 4.58).

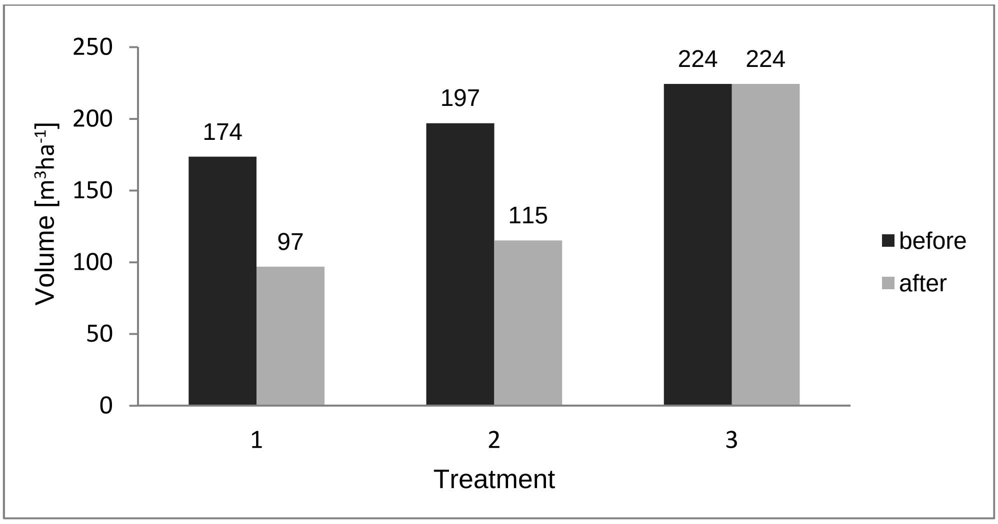

Fig. 4.58 Stand volume in the Middle Branch East before and after the harvest in 2004 for different thinning treatments: 1- removal of every third row plus one in three dominant or codominant trees, 2- removal of every third row plus one in five dominant or codominant trees, 3- no thinning (control plot).

Average stand volume increased with decreasing thinning intensity and was approximately twice larger in control plot compared to thinned plots across entire measurement period (Fig. 4.59). Analogous dependence on thinning grade was noticed to 2-year volume increment (Fig. 4.60), but totally reversed for ratio of 2-year volume increment to standing volume (Fig. 4.61). The most rapid increase in 2-year volume increment ratio was observed for the most intensive thinning (treatment 1).

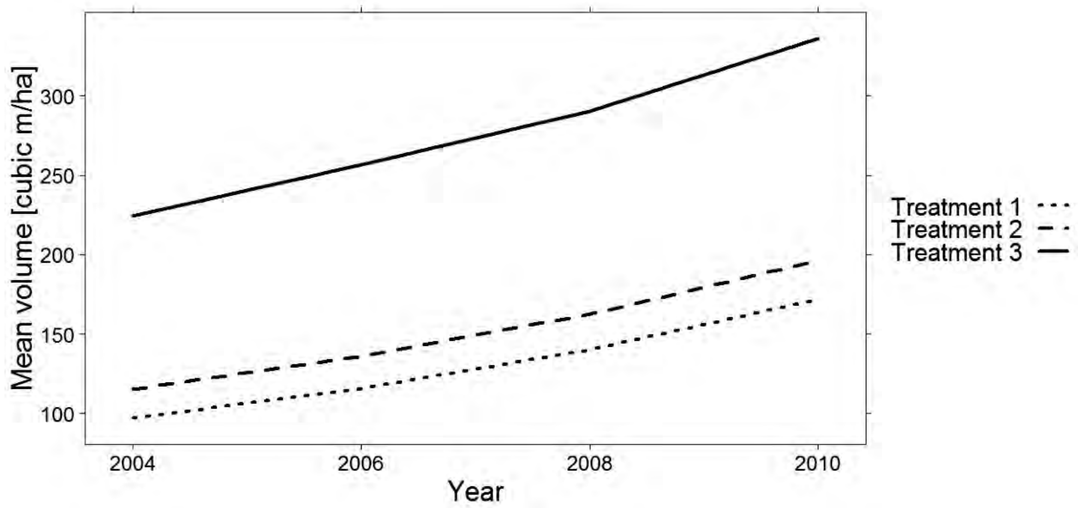

Fig. 4.59 Mean volume in the Middle Branch East. Lines represent treatments: 1- removal of every third row plus one in three dominant or codominant trees, 2- removal of every third row plus one in five dominant or codominant trees, 3- no thinning (control plot).

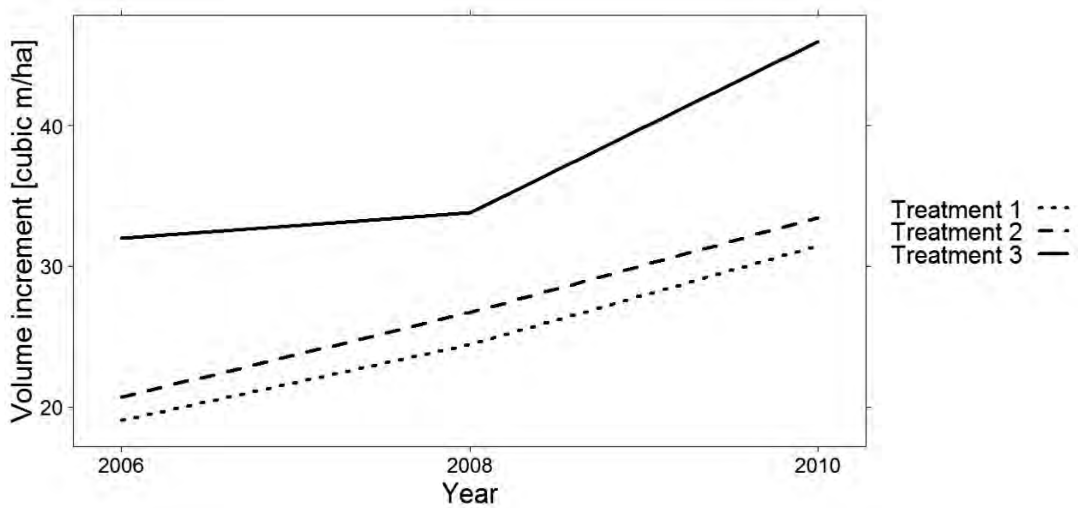

Fig. 4.60 Mean 2-year volume increment in the Middle Branch East. Lines represent treatments: 1- removal of every third row plus one in three dominant or codominant trees, 2- removal of every third row plus one in five dominant or codominant trees, 3- no thinning (control plot).

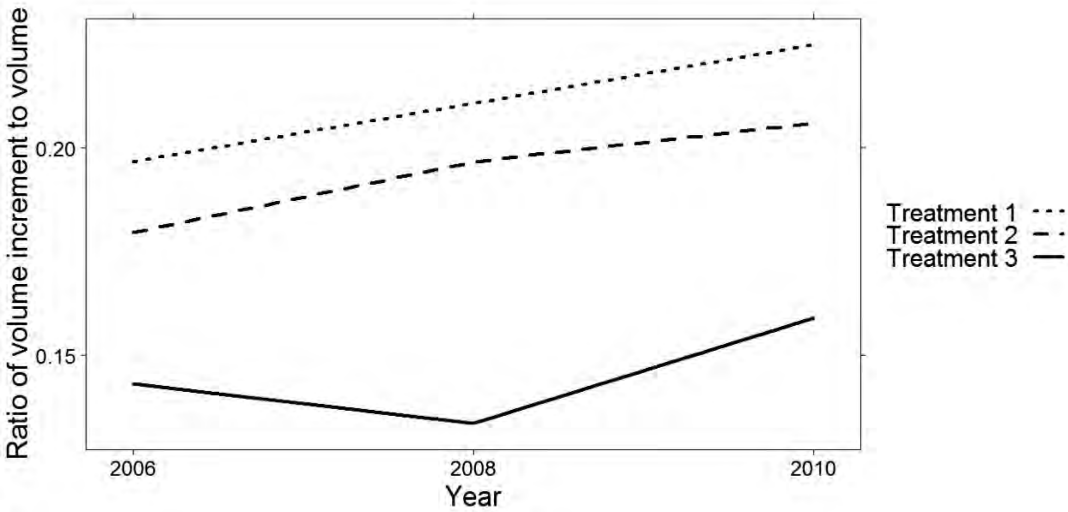

Fig. 4.61 Ratio of 2-year volume increment to standing volume in the Middle Branch East. Lines represent treatments: 1- removal of every third row plus one in three dominant or codominant trees, 2- removal of every third row plus one in five dominant or codominant trees, 3- no thinning (control plot).

The results of ANOVA are presented in Table 4.17. Significant difference between treatments occurred in every year of measurements, however due to significant interaction between blocks and treatments (Fig. 9.3), the Tukey test was performed only for years: 2006 and 2010 (Fig. 4.62).

Table 4.17
The analysis of variance results for 2-year volume increment in the Middle Branch East.

Year	Source	Degrees of freedom	Sum of squares	MSE (mean square error)	F value	Pr (>F)	Bartlett test (p value)
	Treatments	2	1193.46	596.73	32.9692	**4.369e-08***	
2006	Block	2	2.23	1.11	0.0616	0.9404	0.2375
	Residuals	28	506.79	18.10			
	Treatments	2	571.83	285.91	16.5259	**1.822e-05***	
2008	Block	2	59.73	29.87	1.7263	0.1963	0.6815
	Residuals	28	484.43	17.30			
	Treatments	2	1493.84	746.92	22.7057	**1.38e-06***	
2010	Block	2	135.08	67.54	2.053	0.1472	0.3787
	Residuals	28	920.08	32.90			

*significant on the significance level α=0.05

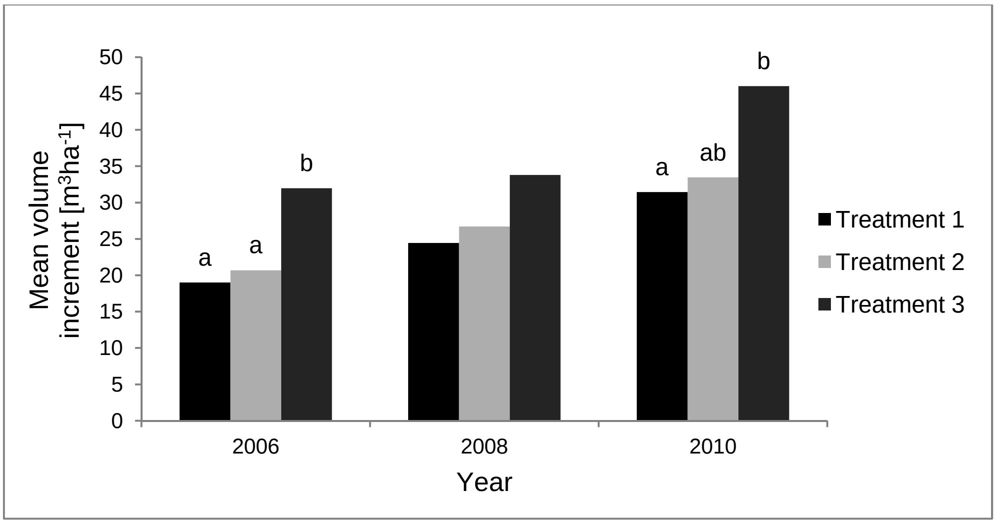

Fig. 4.62 Mean 2-year volume increment in the Middle Branch East for different years and treatments: 1- removal of every third row plus one in three dominant or codominant trees, 2- removal of every third row plus one in five dominant or codominant trees, 3- no thinning (control plot). Different letters above bars indicate significant differences between means according to the Tukey test. Lack of letters above bars indicates significant blocks- treatments interaction.

The analysis of variance gave similar results for ratio of 2-year volume increment to standing volume (Table 4.18), though the Tukey test was performed to all years (Fig. 4.63).

Table 4.18
The analysis of variance results for ratio of 2-year volume increment to standing volume in the Middle Branch East

Year	Source	Degrees of freedom	Sum of squares	MSE (mean square error)	F value	P (>F)	Bartlett test (p value)
	Treatments	2	0.017991	0.0089955	22.8321	**1.314e-06***	
2006	Block	2	0.000744	0.0003719	0.9439	0.4012	0.6868
	Residuals	28	0.011032	0.0003940			
	Treatments	2	0.040612	0.0203058	70.5330	**1.168e-11**	
2008	Block	2	0.003907	0.0019534	6.7853	**0.003956**	0.1142
	Residuals	28	0.008061	0.0002879			
	Treatments	2	0.027630	0.0138149	34.0730	**3.156e-08**	
2010	Block	2	0.005653	0.0028266	6.9714	0.003491	0.8088
	Residuals	28	0.011353	0.0004055			

*significant on the significance level α=0.05

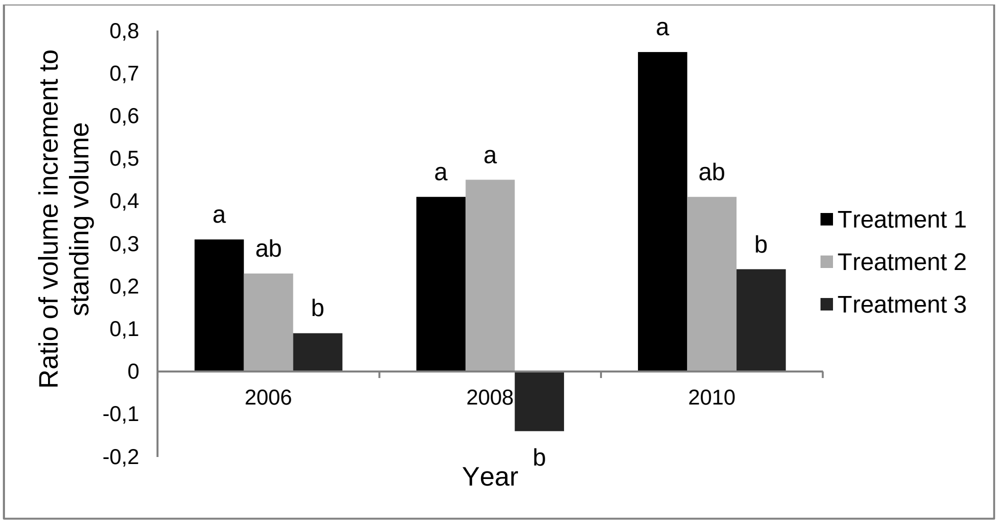

Fig. 4.63 Mean ratio 2-year volume increment to standing volume in the Middle Branch East for different years and treatments: 1- removal of every third row plus one in three dominant or codominant trees, 2- removal of every third row plus one in five dominant or codominant trees, 3- no thinning (control plot). Different letters above bars indicate significant differences between means according to the Tukey test. Lack of letters above bars indicates significant blocks-treatments interaction.

4.8 Relationships between stand characteristics in time

4.8.1 Diameter at breast height and height

There was strong correlation between diameter at breast height and tree height for all treatments (Fig. 4.64, Fig. 4.65, Fig. 4.66). Most commonly the weakest relationship occurred for controls. In most examined years the strongest relationship between these attributes occurred in stands thinned to lowest values of residual basal area. The exception was the Crane Lake trial, where in the beginning of the measurement period the strongest relationship between these attributes occurred for simple row thinning. In the case of thinning from below performed in the Crane Lake trial, correlation coefficient was similar to control plot over the measurement period.

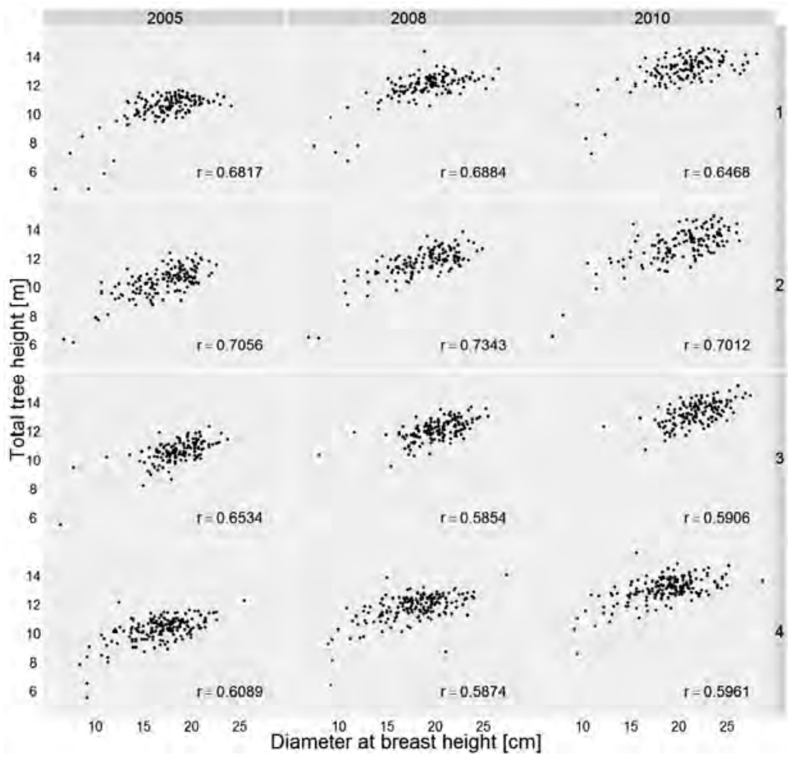

Fig. 4.64 Tree height in relation to diameter at breast height in time for the Atlantic Mine. Rows represent treatments: 1- removal of every fifth row plus crown thinning, 2- removal of every third row plus crown thinning, 3- removal of every third row plus thinning from below, 4- no thinning (control plot). r- Pearson correlation coefficient.

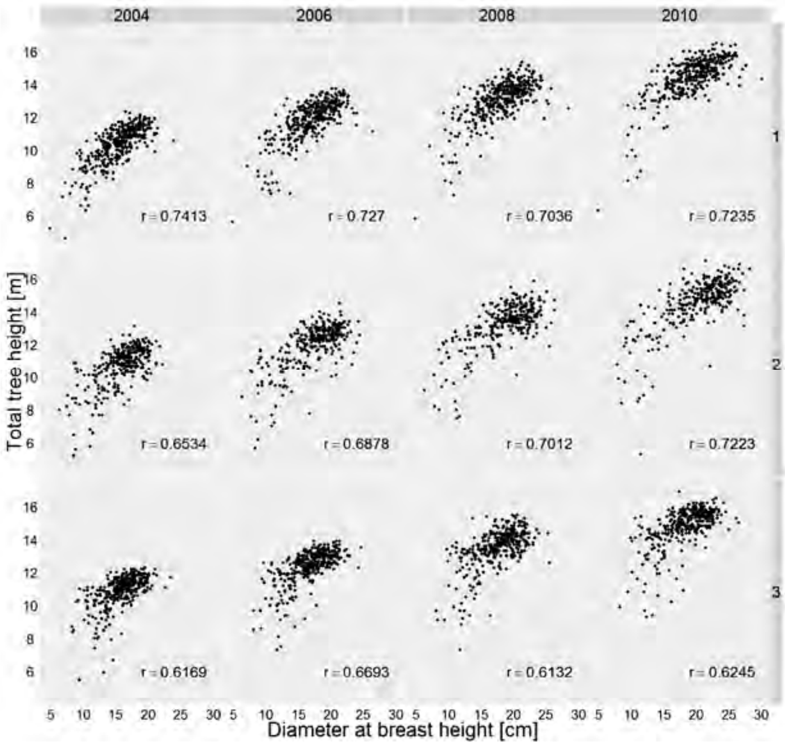

Fig. 4.65 Tree height in relation to diameter at breast height in time for the Crane Lake. Rows represent treatments: thinning treatments: 1- removal of every third row, 2- removal of every third row and crown thinning, 3- no thinning (control plot). r- Pearson correlation coefficient.

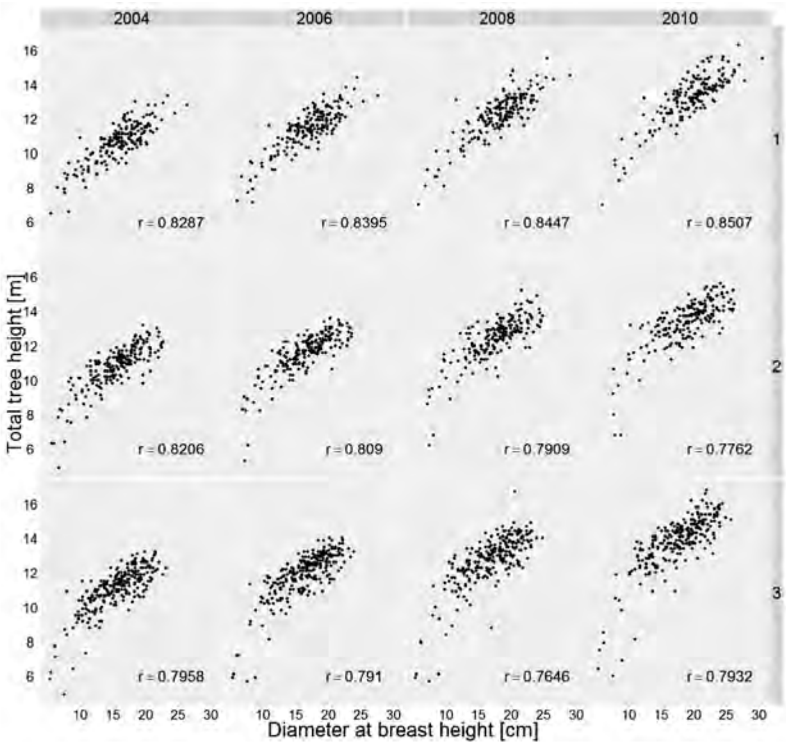

Fig. 4.66 Tree height in relation to diameter at breast height in time for the Middle Branch East. Rows represent treatments: 1- removal of every third row plus one in three dominant or codominant trees, 2- removal of every third row plus one in five dominant or codominant trees, 3- no thinning (control plot). r- Pearson correlation coefficient.

4.8.2 Diameter at breast height and live crown length

Strong relationship between live crown length and diameter at breast height occurred for all treatments in all years and had a tendency to increase with decreasing stand density. However there was no clear change in time, the values of r were fluctuating (Fig. 4.68, Fig. 4.69). In the case of the Atlantic mine trial, Pearson's r for treatment 1 was decreasing in time, therefore in the end of measurement period r was smaller than for control and thinning from below (Fig. 4.67).

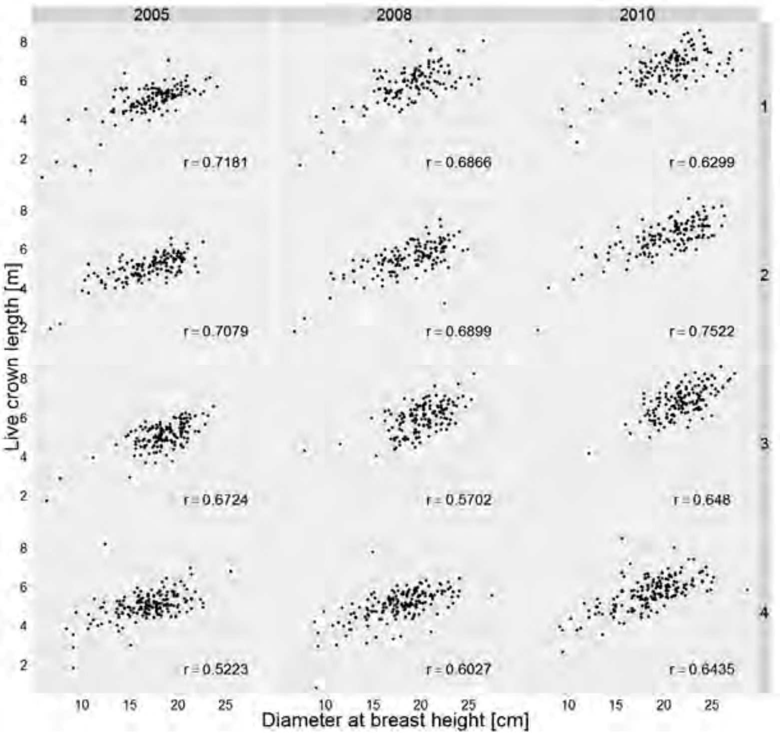

Fig. 4.67 Live crown length in relation to diameter at breast height in time for the Atlantic Mine. Rows represent treatments: 1- removal of every fifth row plus crown thinning, 2- removal of every third row plus crown thinning, 3- removal of every third row plus thinning from below, 4- no thinning (control plot). r- Pearson correlation coefficient.

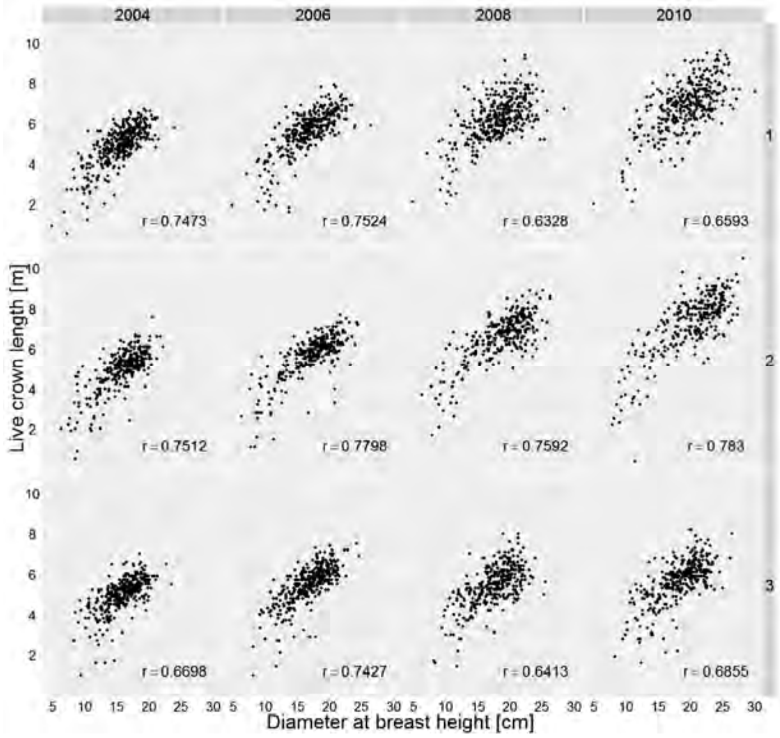

Fig. 4.68 Live crown length in relation to diameter at breast height in time for the Crane Lake. Rows represent treatments: thinning treatments: 1- removal of every third row, 2- removal of every third row and crown thinning, 3- no thinning (control plot). r- Pearson correlation coefficient.

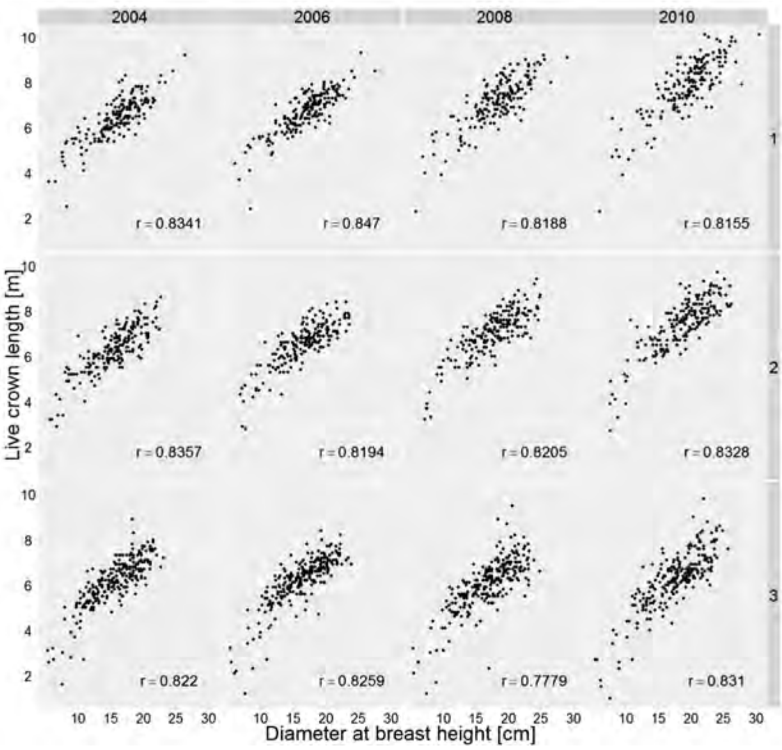

Fig. 4.69 Live crown length in relation to diameter at breast height in time for the Middle Branch East. Rows represent treatments: 1- removal of every third row plus one in three dominant or codominant trees, 2- removal of every third row plus one in five dominant or codominant trees, 3- no thinning (control plot). r- Pearson correlation coefficient.

4.8.3 Average live crown length and stand volume

There was basically no common trend in relationship between average live crown length and stand volume in time, which indicates low dependence of volume on individual tree crown size (Fig. 4.70, Fig. 4.71, Fig. 4.72). Strong relationship between these attributes occurred only for row thinning with crown thinning in the Atlantic Mine trial.

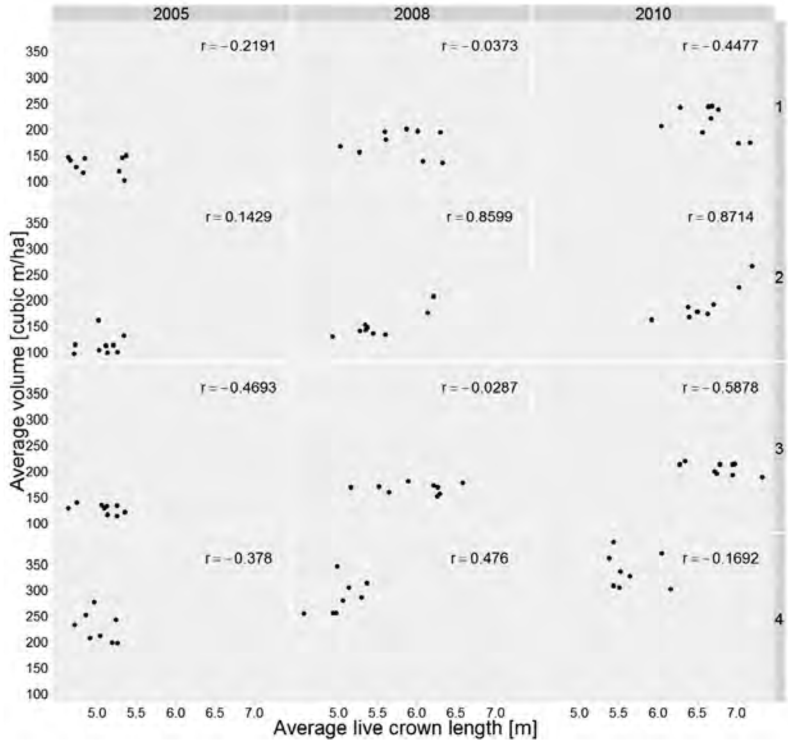

Fig. 4.70 Stand volume in relation to average live crown length in time for the Atlantic Mine. Rows represent treatments: 1- removal of every fifth row plus crown thinning, 2- removal of every third row plus crown thinning, 3- removal of every third row plus thinning from below, 4- no thinning (control plot). r- Pearson correlation coefficient.

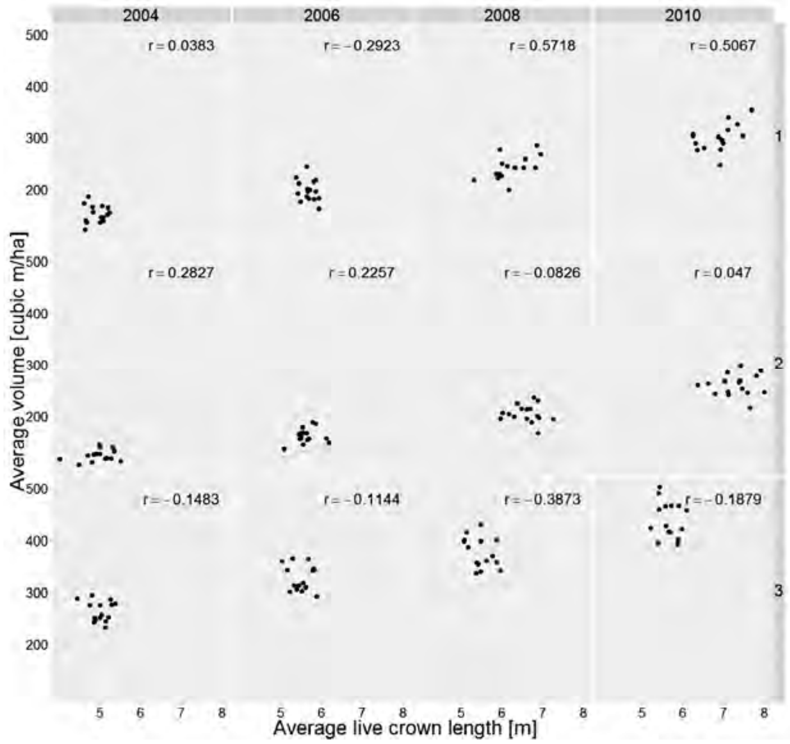

Fig. 4.71 Stand volume in relation to average live crown length in time for the Crane Lake. Rows represent treatments: thinning treatments: 1- removal of every third row, 2- removal of every third row and crown thinning, 3- no thinning (control plot). r- Pearson correlation coefficient.

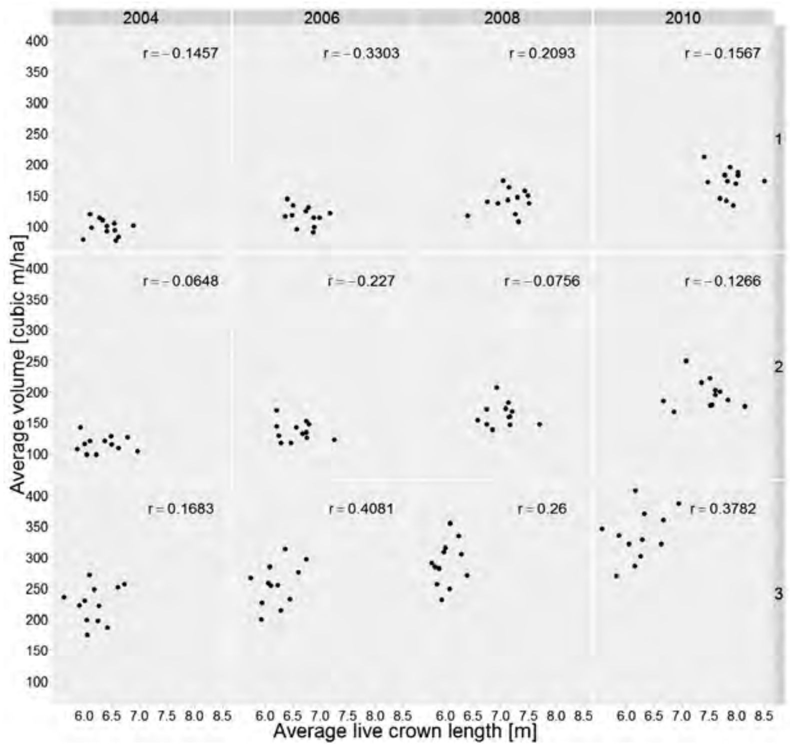

Fig. 4.72 Stand volume in relation to average live crown length in time for the Middle Branch East. Rows represent treatments: 1- removal of every third row plus one in three dominant or codominant trees, 2- removal of every third row plus one in five dominant or codominant trees, 3- no thinning (control plot). r- Pearson correlation coefficient.

4.8.4 Average diameter and stand volume

Very strong relationship between volume per hectare and average diameter was observed for treatment 2 (removal of every third row plus crown thinning) in the Atlantic Mine trial (Fig. 4.73). However, there was no common trend for different years and treatments (Fig. 4.74, Fig. 4.75).

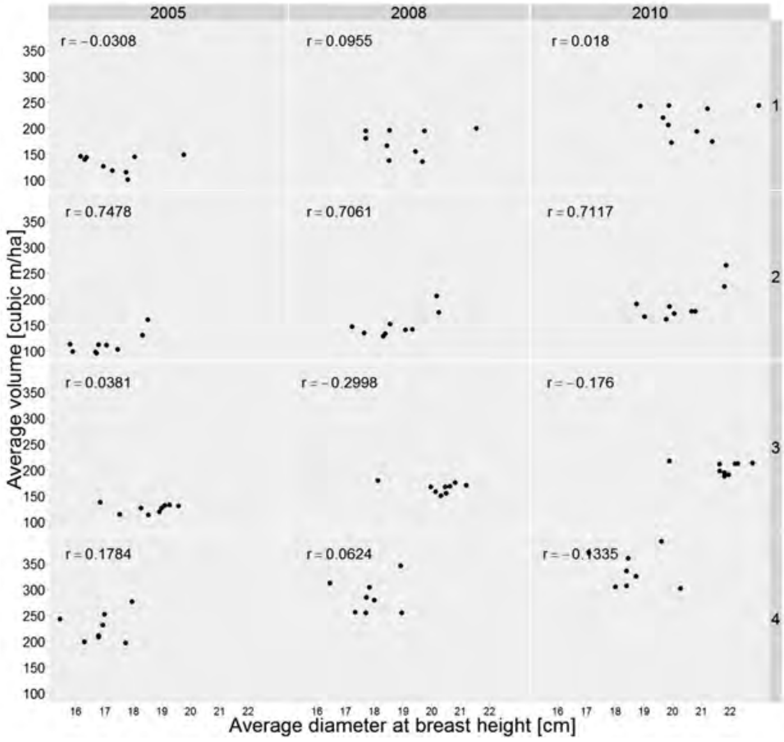

Fig. 4.73 Stand volume in relation to average diameter at breast height in time for the Atlantic Mine. Rows represent treatments: 1- removal of every fifth row plus crown thinning, 2- removal of every third row plus crown thinning, 3- removal of every third row plus thinning from below, 4- no thinning (control plot). r- Pearson correlation coefficient.

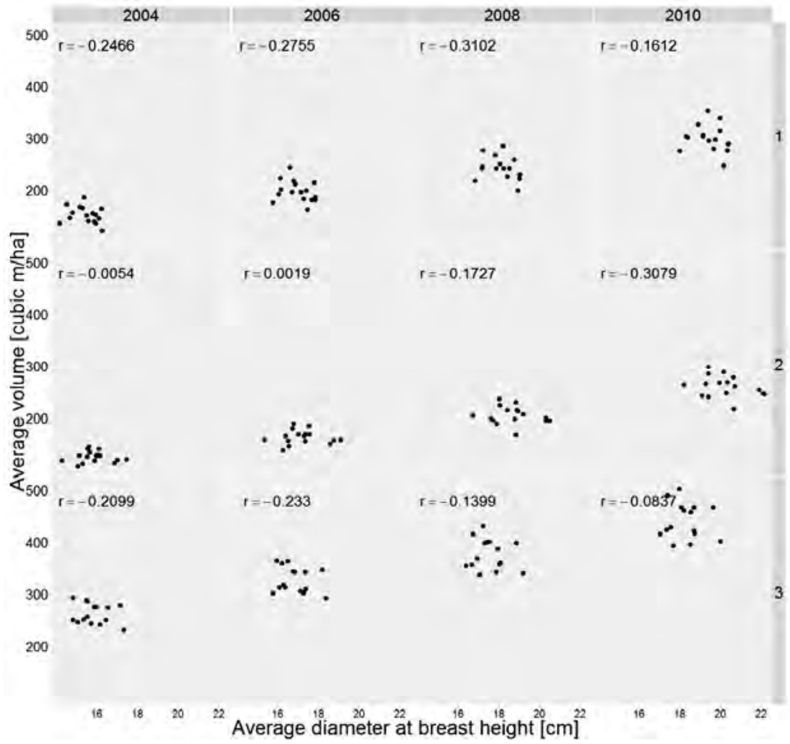

Fig. 4.74 Stand volume in relation to average diameter at breast height in time for the Crane Lake. Rows represent treatments: thinning treatments: 1- removal of every third row, 2- removal of every third row and crown thinning, 3- no thinning (control plot). r- Pearson correlation coefficient.

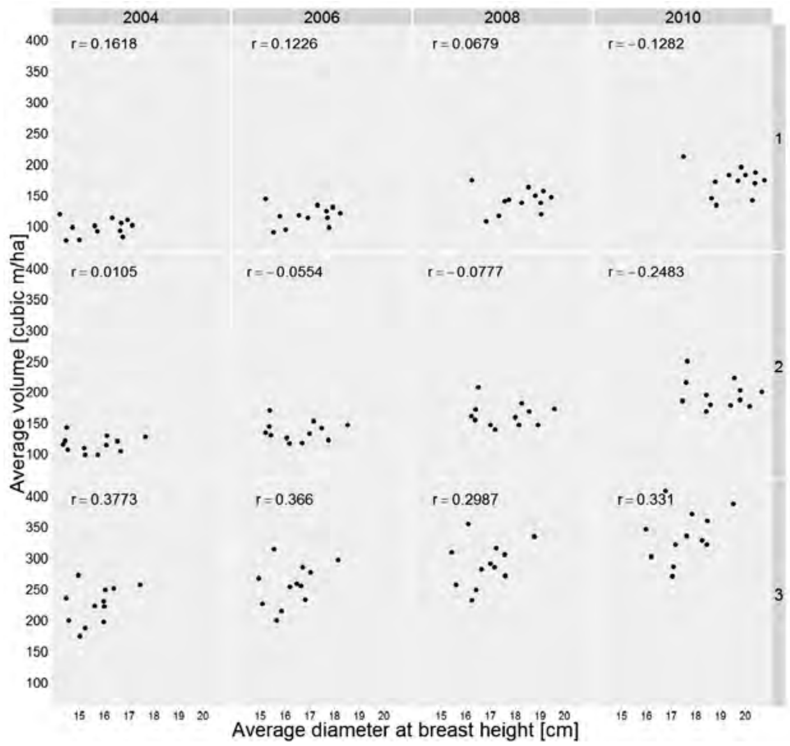

Fig. 4.75 Stand volume in relation to average diameter at breast height in time for the Middle Branch East. Rows represent treatments: 1- removal of every third row plus one in three dominant or codominant trees, 2- removal of every third row plus one in five dominant or codominant trees, 3- no thinning (control plot). r- Pearson correlation coefficient.

4.8.5 Average live crown length and stand basal area

No common trend in relationship between live crown length and basal area in time occurred for analyzed treatments (Fig. 4.76, Fig. 4.77, Fig. 4.78). However, also in this case the exception was removal of every third row plus crown thinning in the Atlantic Mine trial.

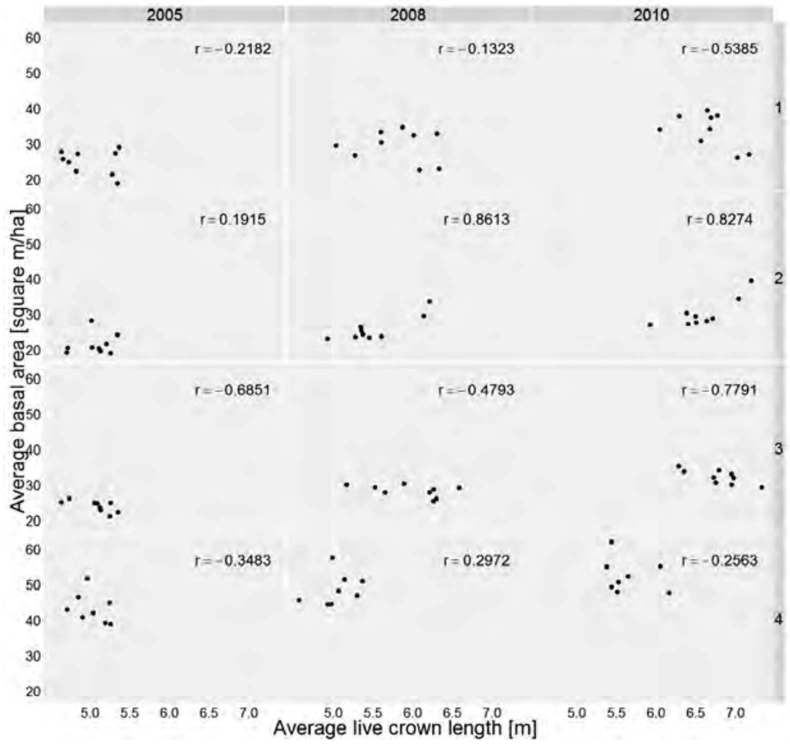

Fig. 4.76 Stand basal area in relation to average live crown length in time for the Atlantic Mine. Rows represent treatments: 1- removal of every fifth row plus crown thinning, 2- removal of every third row plus crown thinning, 3- removal of every third row plus thinning from below, 4- no thinning (control plot). r- Pearson correlation coefficient.

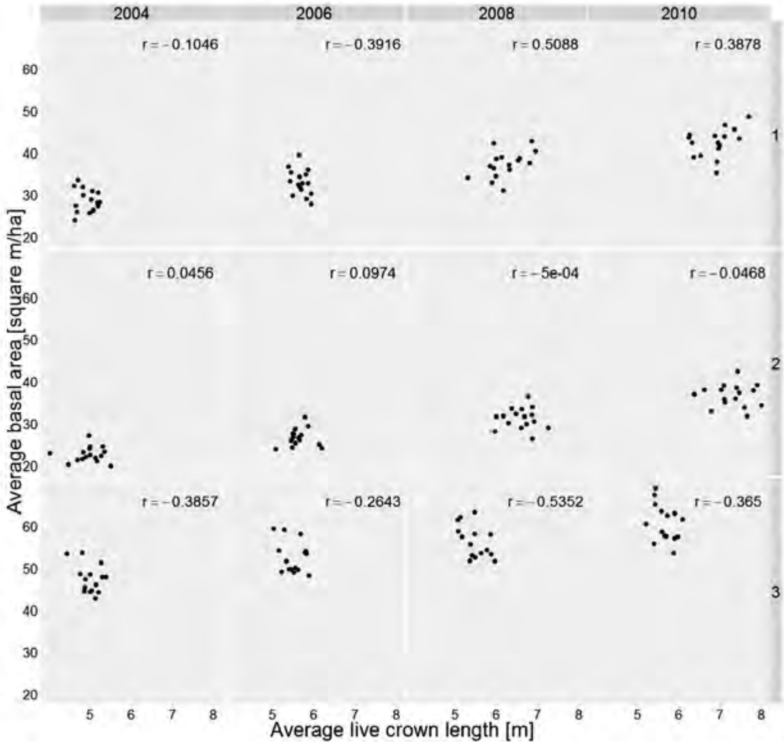

Fig. 4.77 Stand basal area in relation to average live crown length in time for the Crane Lake. Rows represent treatments: thinning treatments: 1- removal of every third row, 2- removal of every third row and crown thinning, 3- no thinning (control plot). r- Pearson correlation coefficient.

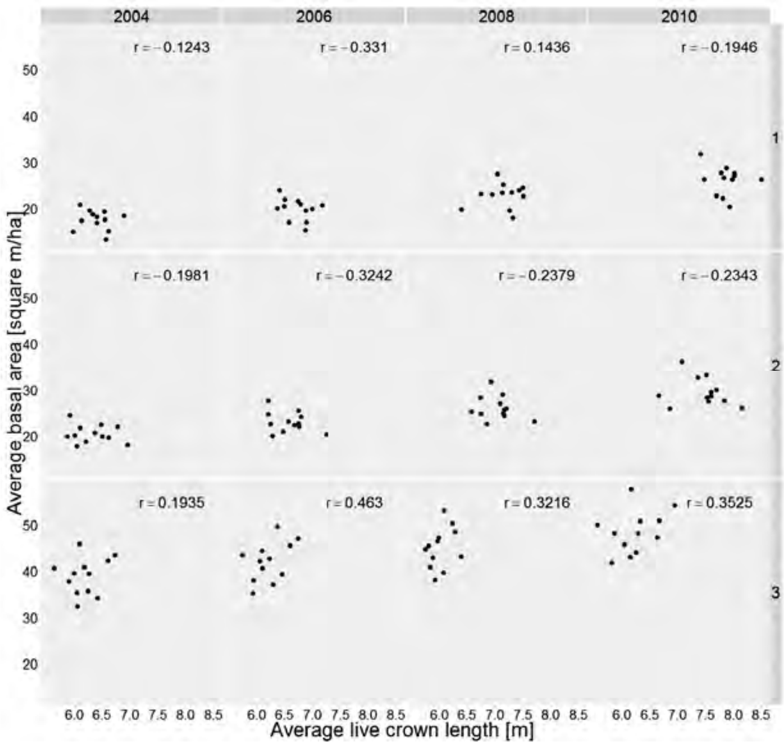

Fig. 4.78 Stand basal area in relation to average live crown length in time for the Middle Branch East. Rows represent treatments: 1- removal of every third row plus one in three dominant or codominant trees, 2- removal of every third row plus one in five dominant or codominant trees, 3- no thinning (control plot). r- Pearson correlation coefficient.

4.8.6 Average height and stand volume

For treatment 2 (every third row removal plus crown thinning) and control plot in the Atlantic Mine, as well as for all treatments in the Middle Branch East positive correlation between average height and average stand volume can be observed (Fig. **4.79**, Fig. 4.81). However there is no common trend with year of measurement or density change. For most of remaining plots weak and negative correlation was noticed (Fig. 4.80).

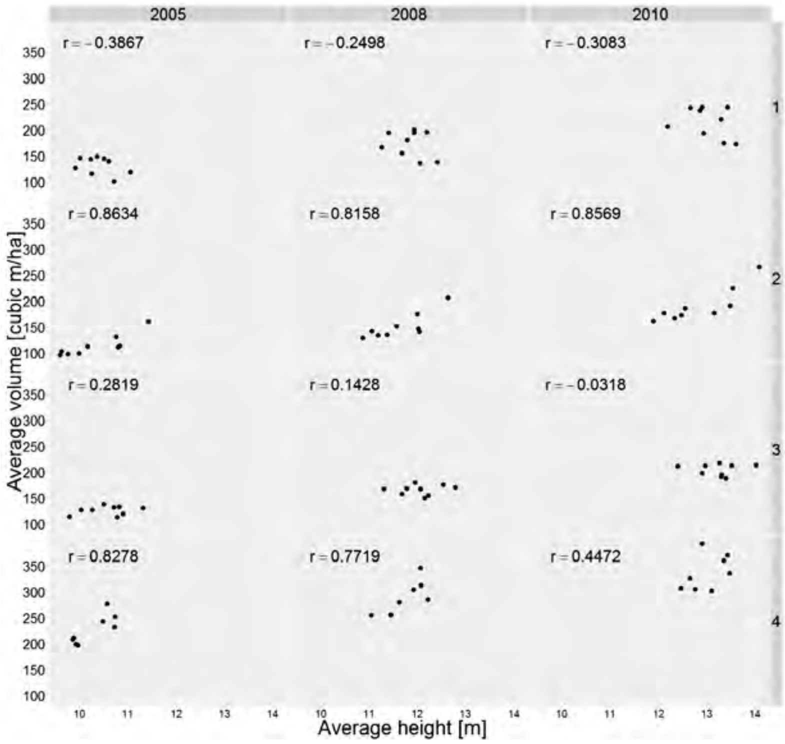

Fig. 4.79 Stand volume in relation to average height in time for the Atlantic Mine. Rows represent treatments: 1- removal of every fifth row plus crown thinning, 2- removal of every third row plus crown thinning, 3- removal of every third row plus thinning from below, 4- no thinning (control plot). r- Pearson correlation coefficient.

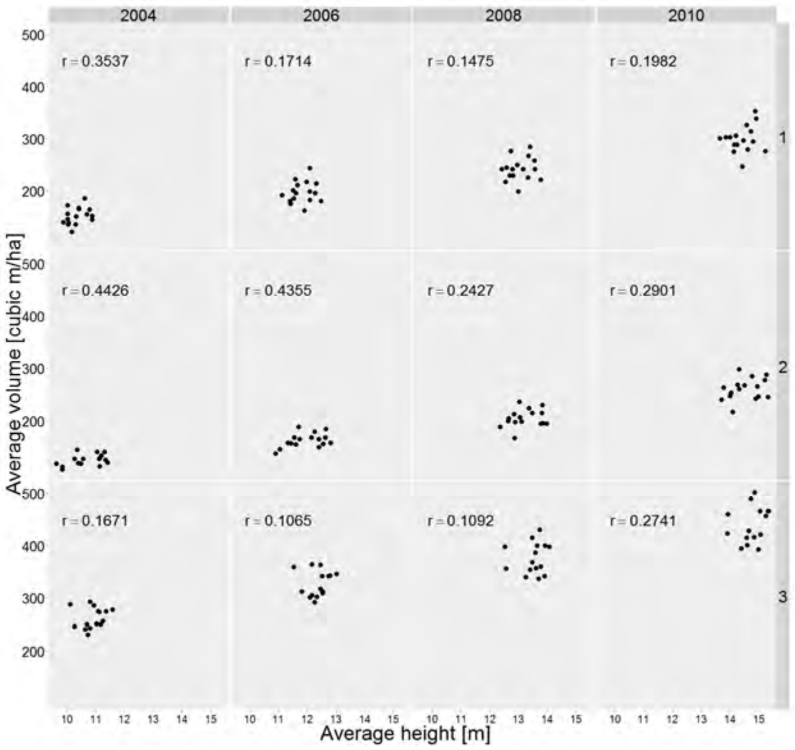

Fig. 4.80 Stand volume in relation to average height in time for the Crane Lake. Rows represent treatments: thinning treatments: 1- removal of every third row, 2- removal of every third row and crown thinning, 3- no thinning (control plot). r- Pearson correlation coefficient.

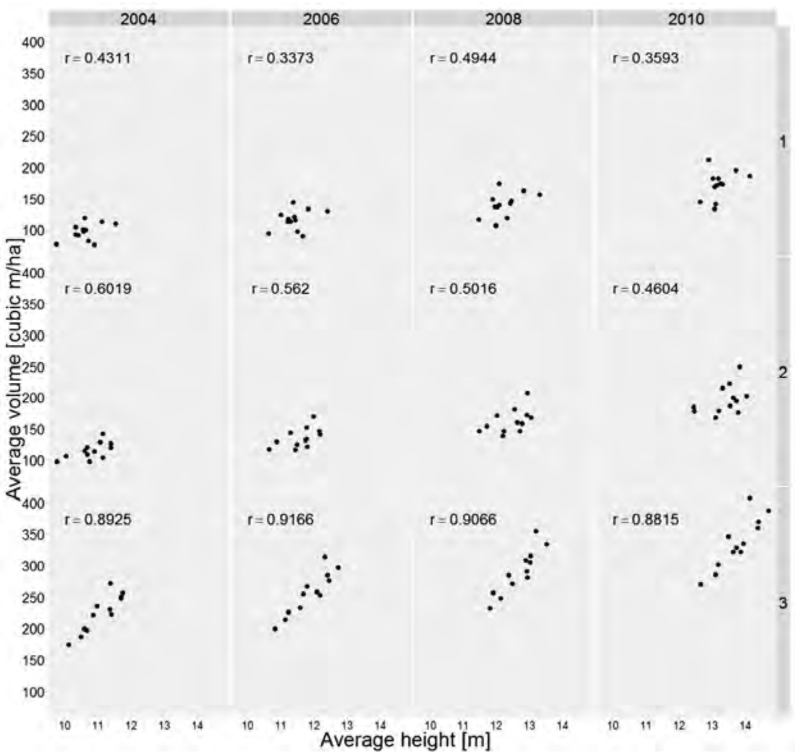

Fig. 4.81 Stand volume in relation to average height in time for the Middle Branch East. Rows represent treatments: 1- removal of every third row plus one in three dominant or codominant trees, 2- removal of every third row plus one in five dominant or codominant trees, 3- no thinning (control plot). r- Pearson correlation coefficient.

4.8.7 Stand volume and stand basal area

Relationship between average volume per hectare and average basal area per hectare was very strong (r close to 1) for all treatments and years (Fig. 4.82, Fig. 4.83, Fig. 4.84). The largest values of correlation coefficient were noticed for controls in both, Crane Lake and Middle Branch East, trials, and for row thinnings with crown release in the Atlantic Mine trial.

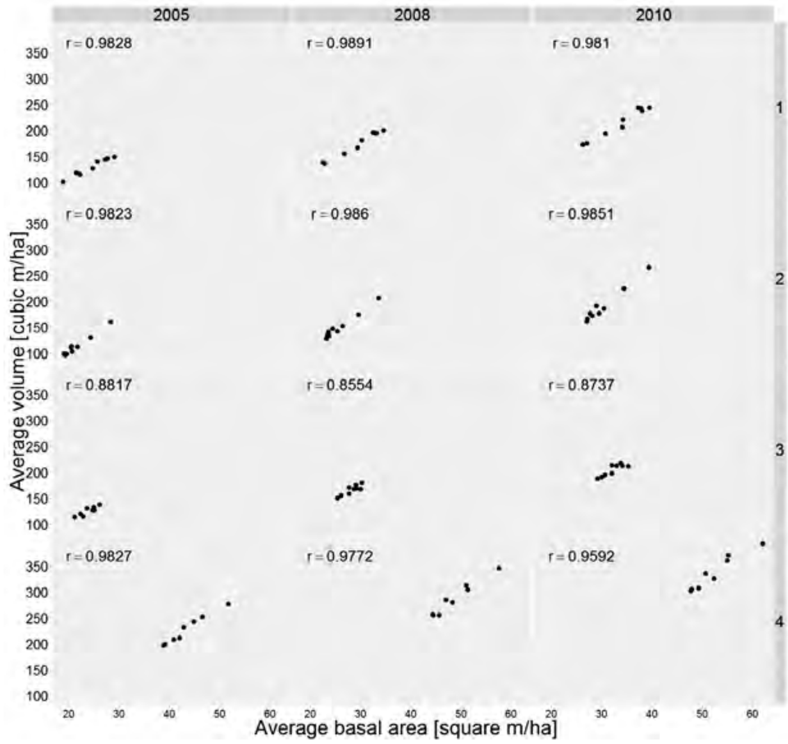

Fig. 4.82 Stand volume in relation to stand basal area in time for the Atlantic Mine. Rows represent treatments: 1- removal of every fifth row plus crown thinning, 2- removal of every third row plus crown thinning, 3- removal of every third row plus thinning from below, 4- no thinning (control plot). r- Pearson correlation coefficient.

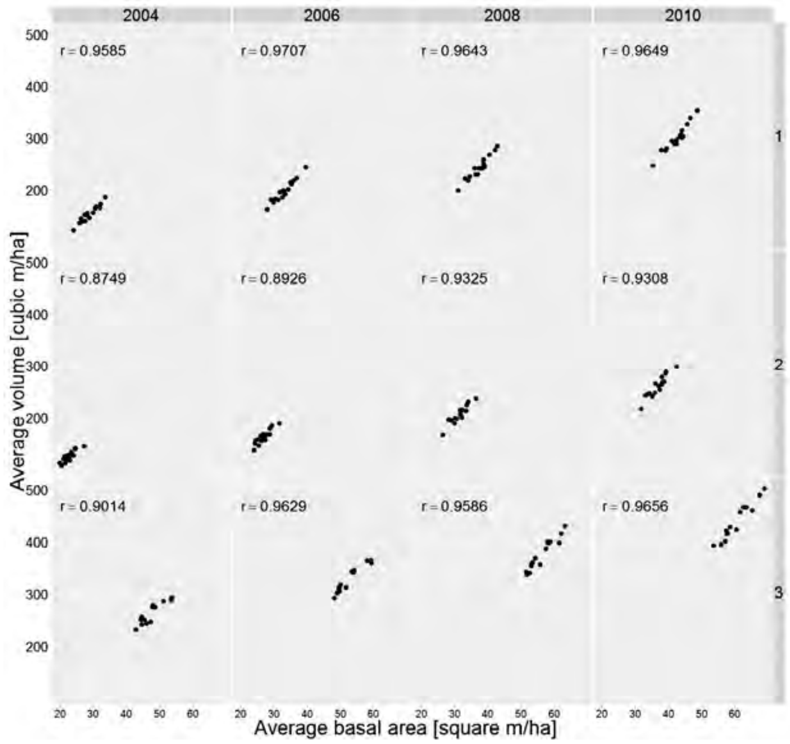

Fig. 4.83 Stand volume in relation to stand basal area in time for the Crane Lake. Rows represent treatments: thinning treatments: 1- removal of every third row, 2- removal of every third row and crown thinning, 3- no thinning (control plot). r- Pearson correlation coefficient.

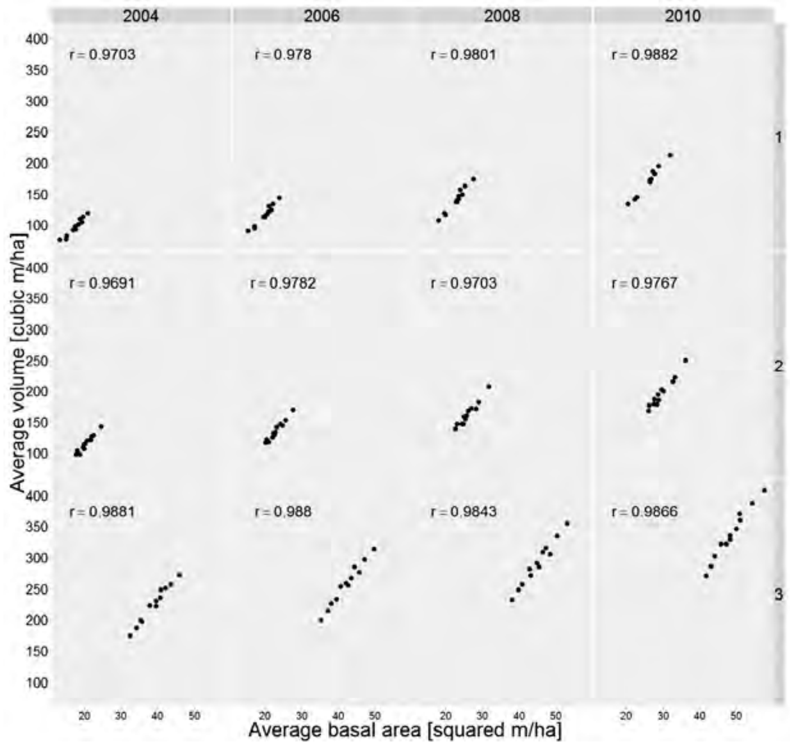

Fig. 4.84 Stand volume in relation to stand basal area in time for the Middle Branch East. Rows represent treatments: 1- removal of every third row plus one in three dominant or codominant trees, 2- removal of every third row plus one in five dominant or codominant trees, 3- no thinning (control plot). r- Pearson correlation coefficient.

5. Discussion

There are only a few publications describing similar experiments in red pine stands, thus the results obtained in the following study will be compared also to other species, especially to Scots pine (*Pinus sylvestris* L.). Moreover, the discussion will focus only on differences between particular treatments in their effect on trees growth, with no analysis of other factors e.g. soil, site type, water availability, climate or site preparation.

5.1 Average diameter at breast height and live crown length

Oliver and Larson (1996) number several factors which are substantial for tree growth. These are: sunlight, water, nutrients, suitable temperatures, oxygen and carbon dioxide. Because of limitations in availability of these factors (mostly due to competition between trees), stand growth also becomes limited. Performing a thinning contributes to reduction of the competition between trees, and as a result to increase in nutrients and water available for individual tree, changes in temperature and climate conditions within a stand. According to Assmann (1970), thinning in even-aged coniferous stands results in increase of live crown size due to extension of growing space and resource availability. Opening stand canopy, results also in acceleration of diameter and tree basal area increment until maximal exploitable space for growth is achieved. One of the reasons for this is mentioned before increased growing space and live crown size, which mean increased area of leaves (photosynthetic area) and reduction of competition.

The results of following experiment are consistent with mentioned findings. Diameter increment is favored to diameter at breast height analysis. The reason for this approach is that average stand diameter after thinning changes not only due to decreased competition, but also due to removal of specific trees: smaller for thinning from below and larger for thinning from above (Cooley 1969). For red pine data analyzed for this thesis, diameter increment is significantly larger in stands treated with row thinning and thinning from above compared to stands where no thinning was applied. However significant difference between thinnings occurred only for several years in the Crane Lake trial (due to thinning from below), which is contrary to Cooley (1969), according to whom red pine plantations are so uniform that removal of any selected trees does not affect diameter growth. For some stands, DBH increment in thinned stands is two or three times as large as in control plots.

In all cases, diameter increment, live crown length and its increment increase with increasing thinning intensity. Therefore, my results show very strong relationship between live crown length and diameter at breast height, which is also stated by Stiell (1966) and Oliver and Larson (1996). However, contrary to Stiell (1966), ratio of crown length to tree height shows clear dependence on stand density only in one trial, the Middle Branch East. Increase in diameters growth due to increasing thinning intensity for red pine was observed also by Cooley (1969); Liechty et al. (1985) and D’Amato et al. (2010). Similar results about the effect of thinning versus no thinning in relationship to changes in stand density on diameter increment for Scots pine were obtained by Mäkinen and Isomäki (2004) and Nilsson et al. (2010). There was only one case when thinning from below was applied. This resulted in larger diameters due to removal of smaller trees, which is called “chainsaw effect” (Pelletler and Pitt 2008) and which might contribute to lowering rotation age. Nevertheless, thinning from above is preferred to thinning from below due to higher increment rates related to smaller trees that are not removed in a treatment (Cooley 1969; Assmann 1970; Buckman 2006).

Thinning treatments result in change in diameter distribution. Baldwin et al. (2000) found out that the percentage of trees in higher diameter classes in loblolly pine stands increases with increasing thinning intensity. Results of following study show the shift towards larger diameter classes for thinning treatments compared to controls. However, the main difference between thinning treatments was number of trees in particular diameter classes, not substantial skew towards any class. The exception was thinning from below, in the Atlantic Mine trial, which resulted in substantial decrease in number of trees in smaller classes, which caused shift towards larger diameter classes (Bradford and Palik 2009). Additionally, there was major similarity between diameter distributions (but certainly number of trees was different) for control plot and row thinning in the Crane Lake trial. The reason for this parallel is that, due to no selection in a row thinning, trees in all diameter classes are removed, thus these stands are more diverse in structure compared to other treatments.

5.2 Stand basal area

Individual tree basal area increment responds to thinning similarly to diameter increment (Assmann 1970). In the case of following study, stand basal area is presented in square meters per hectare. This is why results are reverse to those representing individual trees, since stand basal area depends rather on number of trees than on trees diameters, hence it is the largest in control plots. Moreover, in most cases there is very weak, and often negative, relationship between average live crown length and average basal area per hectare, which also indicates that at this stage of the analysis, number of trees has the largest importance in stand basal area value compared to other stand attributes. According to Buckman et al. (2006), basal area in red pine stands till age of 20-30 years is substantially dependent on number of stems, whereas in older stands becomes more homogeneous in spite of densities (expressed in trees per area). This remark might be observed in the Middle Branch East trial, where trees were planted 33 years ago stand basal area increment in recent years differs among treatments only slightly, and this difference declines in time. Stands in remaining trials are 26-27 years old and these trends are not observed yet. Nonetheless, this assumption is based on a short-time observation. Despite larger basal area in stands thinned from below in the Atlantic mine trial compared to thinning from above, trend for stand basal area increment is opposite, which is consistent with Buckman et al. (2006). They summarize their findings about BA that stands thinned with crown thinning produced more basal area than stands where thinning from below was applied.

5.3 Average tree height

For majority of stands which were examined in following thesis, the largest heights and height increments occur in control plots, whereas the lowest in stands where the most intensive thinnings were applied. However, these are only slight and non-significant differences, therefore the results of this study show height increment’s independence of thinning intensity. Moreover, difficulties in interpretation of these results appear due to significant blocks- treatments interactions. Nevertheless, for example in Middle Branch East it is possible to notice clearly that the average height and its increment increases with decreasing thinning intensity. These results are consistent with Assmann (1970) who explains how increasing thinning intensity reduces average tree height: too severe opening causes higher increment of diameter, but no additional height growth, unless a thinning is performed before the culmination of increment. This is the effect of widening of growing space, which causes reduction of competition for resources. Besides, Oliver and Larson (1996) refer to several studies showing that height increment is relatively independent of growing space unless the spacing is exceptionally narrow. Mäkinen and Isomäki (2004) obtained similar results about height of Scots pine- the higher thinning grade, the smaller height increment. Their results showed statistical significance especially between unthinned and the heaviest thinned stands. However the stands their analyzed were regenerated naturally (so densely), which may be the reason for differences in height growth.

5.4 Stand volume

Standing volume and its increment increased with decreasing thinning intensity. These results are supported also by Buckman (2006) as well as by Liechty (1985) who found no significant difference between average volume in red pine stands thinned with 7 different treatments, but it was increasing with increasing stand density expressed as basal area. Similar results were obtained for Scots pine by Mäkinen and Isomäki (2004). Very high positive correlation between stand basal area and stand volume occurs also for trials analyzed in this thesis. According to Stiell (1966), there is no clear relationship between crown length and stand volume which is also the result of this study. Similar findings concern the relationship of stand volume to both average diameter and average tree height. These results underline the importance of number of stems prior to other stand attributes in changes in stand volume.

When comparing thinning from below to thinning from above, which were performed along with every third row removal in the Atlantic Mine trial, it can be noticed that, despite similar volumes before and after harvesting in 2006, differences between volumes and volume increments between these treatments increase over the measurement period and are slightly larger for crown thinning, which is analogous to results obtained by Bradford and Palik (2009). These differences are even bigger when ratio of volume increment to standing volume is taken into consideration: its values are almost the same in the beginning but begun to recede in time. These findings are opposite to results achieved by Emmingham et al. (2007) for Douglas fir. In this study thinning from below is recommended as a treatment favoring volume growth over thinning from above. On the other hand, thinning from above is favored, since larger trees are removed, while smaller which have higher relative productivity are left in a stand (Nilsson and Albrektson 1994).

6. Conclusions

According to Ek et al. (2006), growth of red pine is more dependent on stand density after the thinning than on thinning type. Bradford and Palik (2009) found that stand response depends not only on thinning type, but also on stocking level and stand age. These findings support a statement that results of following study should be considered mainly for particular conditions of similar stands. Preliminary suggestions are proposed further in this chapter. The attributes having the largest input to economic thinning assessment are considered: stand volume and volume increment as well as tree sizes expressed by diameter due to no significant difference in height among treatments.

6.1 The Atlantic Mine Thinning Trial

Mean diameter is the largest for thinning from below, which is a result of harvesting trees from smaller diameter classes. Average increment is not significantly different among treatments, but is slightly larger for the most intensive treatment (every third row removal plus crown thinning). In the case of volume, the largest and increasing most dynamically, ratio of 1-year volume increment to standing volume was observed also for the most intensive thinning. This is why, at this stage of the analysis, the heaviest thinning is the most favorable for stand growth.

6.2 The Crane Lake Thinning Trial

Treatment 2 (row thinning plus thinning from above), which was the heaviest thinning, resulted in the largest average diameter and significantly largest DBH increment. 2-year volume increment was smaller than after simple row thinning, however ratio of 2-year volume increment to standing volume was the largest (though not significantly). What is also important is that this treatment provides uniform spatial distribution of trees in the stand, which is very advantageous for their growth. Therefore, it may be concluded that row thinning with thinning from above in residual rows affected stand and trees growth most favorably.

6.3 The Middle Branch East Thinning Trial

Average diameter and its increment were the largest, although not significantly, for the most intensive treatment, removal of every third row and every third tree in remaining rows. 2-year volume increment was the smallest but ratio of increment to standing volume was the largest (but significantly different only from the control plot). Nevertheless this treatment resulted in relatively row residual basal area, which is around minimum according to stocking chart (Benzie 1977). This might not be advantageous for stand growth and stability. Therefore, at this point of the treatments analysis, I assume that treatment 2 (removal of every third thinning and one in five trees) has the most favorable effect on trees and stand growth.

The above conclusions are based only on short-term growth rates observations. Nevertheless, it should be remembered, that financial return of performed thinning does not depend only on volume and diameter increment affected by a thinning. Additional factors could be analyzed, for example timing of the first thinning or susceptibility of heavily thinned stands to wind damages. Detailed financial analysis based on achieved results about stand and trees response to alternative thinning regimes should be performed.

7. Future work

The following study aimed at the analysis of growth response to thinning during 6—7 years after the first harvest. The results have an essential value in widening the knowledge about the effects of thinning treatments on a tree and stand growth within initial period after the first thinning. The analysis does not include year 2011, since the measurements were performed while working on this study. However, including recent data to this analysis would be advantageous, as it could give a chance to observe additional significant differences between treatments in their effect on trees growth and also extra information about growing trends.

The second thinning in analyzed stands will be performed in 2012. It is extremely important to continue this study till the final harvest. This analysis will give detailed information about red pine stands development, which will be vital in preparing thinning guide for stands planted on similar sites and with similar densities.

Following thesis presents information about gross production, which gives important information about whole stand, in spite of situation on the market which might change. Nonetheless, it would be beneficial to prepare the same type of analysis for merchantable wood so the results give more detailed information about the amount of wood of desirable size.

It would be very interesting to perform similar analysis for the same stands divided into diameter or crown classes. This would be valuable in increasing the knowledge about growth responses of trees of different sizes to alternative treatments.

Next part of the analysis of growth response to thinning will be appropriate economic evaluation of performed treatments based on results obtained in this thesis and in future analysis. This would be crucial in making decision about the most profitable thinning in each trial.

8. References

Assman E. 1970. The Principles of Forest Yield Study. Oxford: Pergamon Press Ltd.

Atwell RC, Schulte LA, Palik BJ. 2008. Songbird response to experimental retention harvesting in red pine (*Pinus resinosa*) forests. Forest Ecology and Management. 255(10):3621-3631.

Baldwin VC, Peterson KD, Clark III A, Ferguson RB, Strub MR, Bower DR. 2000. The effects of spacing and thinning on stand and tree characteristics of 38-year-old Loblolly Pine. Forest Ecology and Management. 137(1-3):91-102.

Benzie JW. 1977. Manager's handbook for red pine in the north central States. General Technical Report NC-33. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station.

Bradford JB, D'Amato AW, Palik BJ, Fraver S. 2010. A new method for evaluating forest thinning: growth dominance in managed *Pinus resinosa* stands. Canadian Journal of Forest Research. 40:843-849.

Bradford JB, Palik BJ. 2009. A comparison of thinning methods in red pine: consequences for stand-level growth and tree diameter. Rapid communication: Canadian Journal of Forest Research. 39:489-496.

Buckman RE, Bishaw B, Hanson TJ, Benford FA. 2006. Growth and Yield of Red Pine in the Lake States. General Technical Report NC-271. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station.

Burger TL, Kotar JA. 2003. Guide to Forest Communities and Habitat Types of Michigan. Madison, WI: Department of Forest Ecology and Management.

Burns RM, Honkala BH. 1990. Silvics of North America: 1. Conifers; 2. Hardwoods. Agriculture Handbook 654. Washington, D.C.: U.S. Department of Agriculture, Forest Service. Vol.2, 877 p.

Cooley JH. 1969. Initial thinning in red pine plantations. Research Paper NC-35. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station.

Curtis RO, Marshall DD. 2000. Why quadratic mean diameter? Western Journal of Applied Forestry. 15:137-139.

D'Amato AW, Palik BJ, Kern CC. 2010. Growth, yield, and structure of extended rotation Pinus resionsa stands in Minnesota, USA. Canadian Journal of Forest Research. 40:1000-1010.

Drobyshev I, Goebel PC, Hixb DM, Corace III RG, Semko-Duncan ME. 2008a. Interactions among forest composition, structure, fuel loadings and fire history: A case study of red pine- dominated forests of Seney National Wildlife Refuge, Upper Michigan. Forest Ecology and Management 256:1723-1733.

Drobyshev I, Goebel PC, Hixb DM, Corace III RG, Semko-Duncan ME. 2008b. Pre- and post-European settlement fire history of red pine dominated forest ecosystems of Seney National Wildlife Refuge, Upper Michigan. Canadian Journal of Forest Research. 38(9):2497-2514.

Ek AR, Katovich SA, Palik BJ. 2006. Red Pine Management Guide. A handbook to red pine management in the North Central Region. Available from: http://nrs.fs.fed.us/fmg/nfmg/rp/glos.html [updated 2006 May 25, cited 2011 Sept 18]

Emmingham W, Fletcher R, Fitzgerald S, Bennet M. 2007. Comparing tree and stand volume growth response to low and crown thinning in young natural Douglas-fir Stands. Western Journal of Applied Forestry. 22(2):124-133.

Farrar JL. 1995. Trees of the northern US and Canada. Ames: Iowa State University Press.

Gilmore DQ, Palik BP. 2006. A revised managers handbook for red pine in the North Central Region. General Technical Report NC-264, St. Paul, MN: U.S. Department of Agriculture Forest Service and University of Minnesota.

Helms JA (editor). 1998. The dictionary of Forestry. Bethesda, MD: Society of American Foresters.

Kutner MH, Nachtseim CJ, Neter J, Li W. 2005. Applied Linear Statistical Models. Fifth Edition. New York: McGraw-Hill/Irwin.

Liechty HO, Mroz GD, Reed DD. 1985. The growth and yield responses of a high site quality red pine plantation to seven thinning treatments and two intervals. Canadian Journal of Forest Research. 16:513-520.

Mäkinen H, Isomäki A. 2004.Thinning intensity and growth of Scots pine in Finland. Forest Ecology and Management. 201:311-325.

Martin J, Lorimer C. 1996. How to manage red pine. Forestry Facts no. 82. Madison, Wisconsin, U.S.A.: University of Wisconsin-Madison Extension.

Nilsson U, Agestam E, Eko PM, Elfving B, Fahlvik N, Johansson U, Karlsson K, Lundmark T, Wallentin C. 2010. Thinning of Scots pine and Norway spruce monocultures in Sweden- Effects of different thinning programmes on stand level gross and net stem volume production. Studia Forestalia Suecica. 219:1-46.

Nilsson U, Albrektson A. 1994. Productivity of needles and allocation of growth in young Scots pine trees of different competitive status. Forest Ecology and Management. 68:209-215.

Oliver CD, Larson BC. 1996. Forest Stand Dynamics. New York: John Wiley and Sons.

Palik BJ, Zasada JC. 2003. An ecological context for regenerating multi-cohort, mixed-species red pine forests. Research Note NC-382. St. Paul, MN, U.S.A.

Pelletler G, Pitt DG. 2008. Silvicultural responses of two spruce plantations to midrotation commercial thinning in New Brunswick. Canadian Journal of Forest Research. 38: 851-867.

Plum Creek Timber Company [Internet]. Seattle (WA): Plum Creek Timber Company. Acres by State, 2011. [uptdated 2011, cited 2011 Sept 22]. Available from: http://www.plumcreek.com/Timberland/

Powers M, Kolka R, Palik B, McDonald R, Jurgensen M. 2011. Long-term management impacts on carbon storage in Lake States forests. Forest Ecology and Management. 262:425-431.

Powers M, Palik BJ, Bradford JB, Fraver S, Webster CR. 2010. Thinning method and intensity influence long-term mortality trends in a red pine forest. Forest Ecology and Management. 260:1138-1148.

R Development Core Team [Internet]. Vienna (Austria): R Foundation for Statistical Computing. R: A language and environment for statistical computing, 2011 [downloaded: 2011 May 20]. ISBN 3-900051-07-0. Available from: http://www.R-project.org/.

Stiell WM. 1966. Red pine crown development in relation to spacing. Publ. 1145. Ottawa, Ontario: Canada Department of Forestry.

Wykoff Gary. 2011. Personal communication.

Youngblood A. 2011. Ecological lessons from long-term studies in experimental forests: Ponderosa pine silviculture at Pringle Falls Experimental Forest, central Oregon. Forest Ecology and Management. 261(5):937-947.

Zar JH. 2010. Biostatistical Analysis. 5th edition. Upper Saddle River, NJ: Pearson Prentice-Hall.

9. Appendix

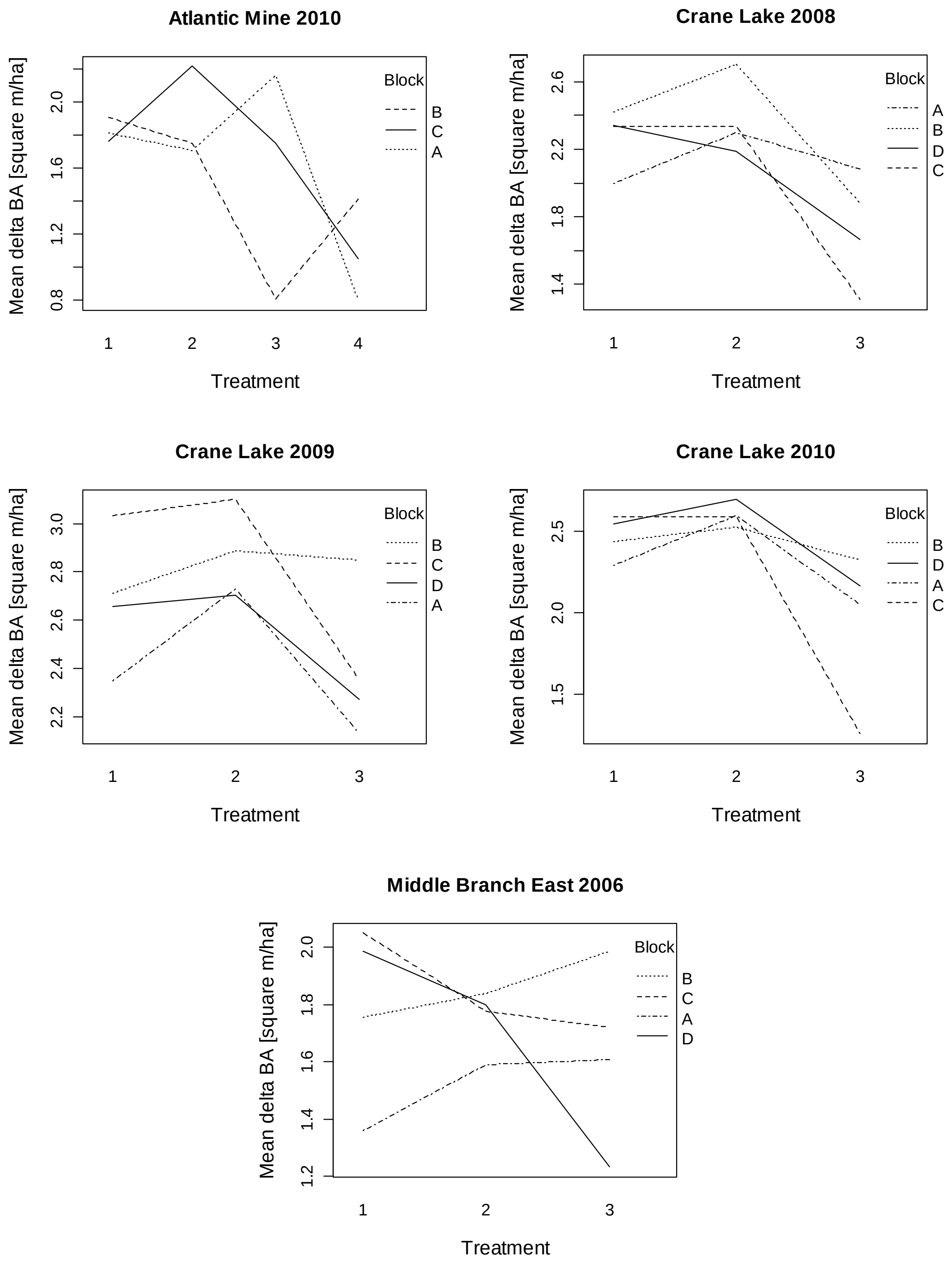

Fig. 9.1 Interaction plots for basal area increment

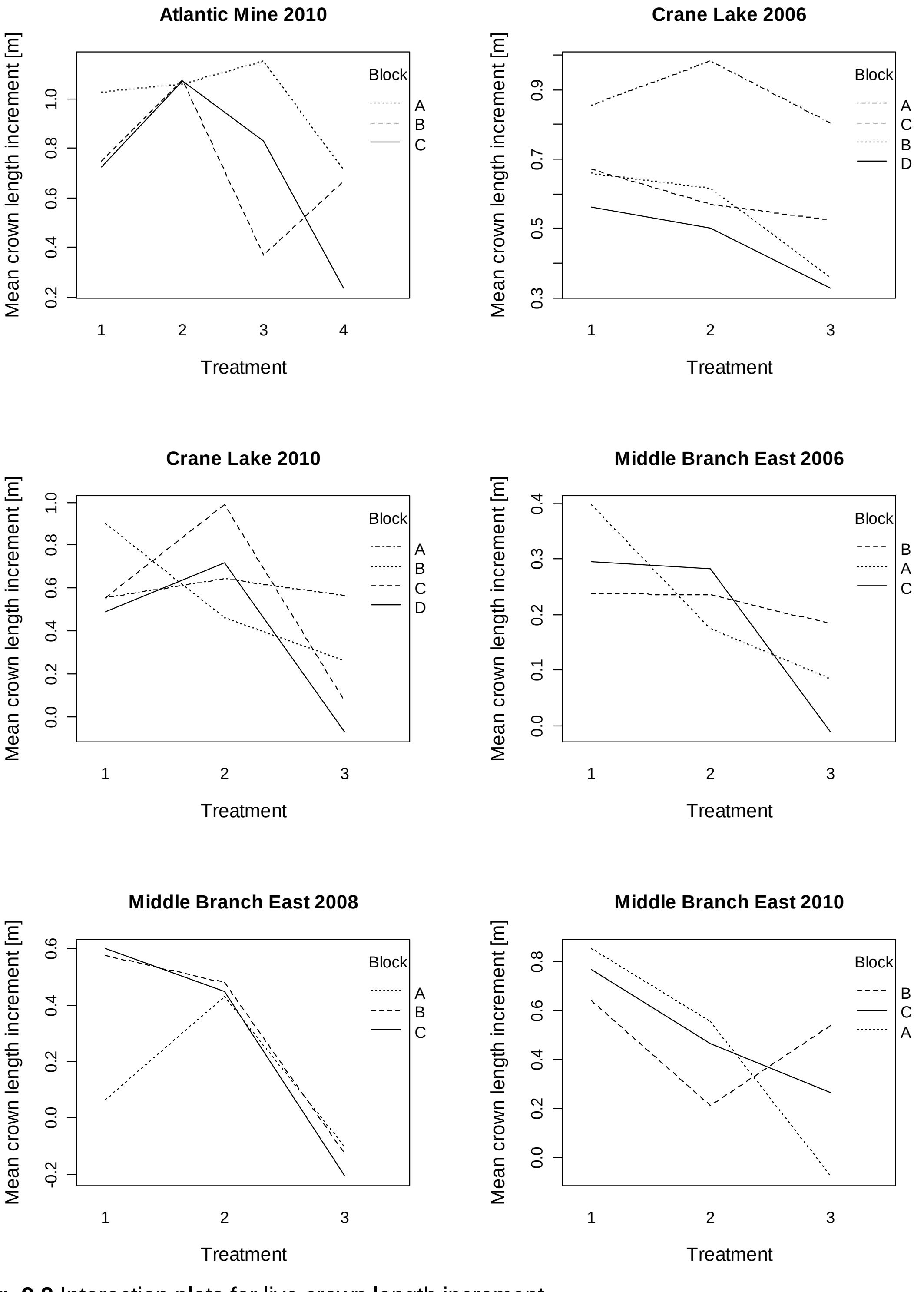

Fig. 9.2 Interaction plots for live crown length increment

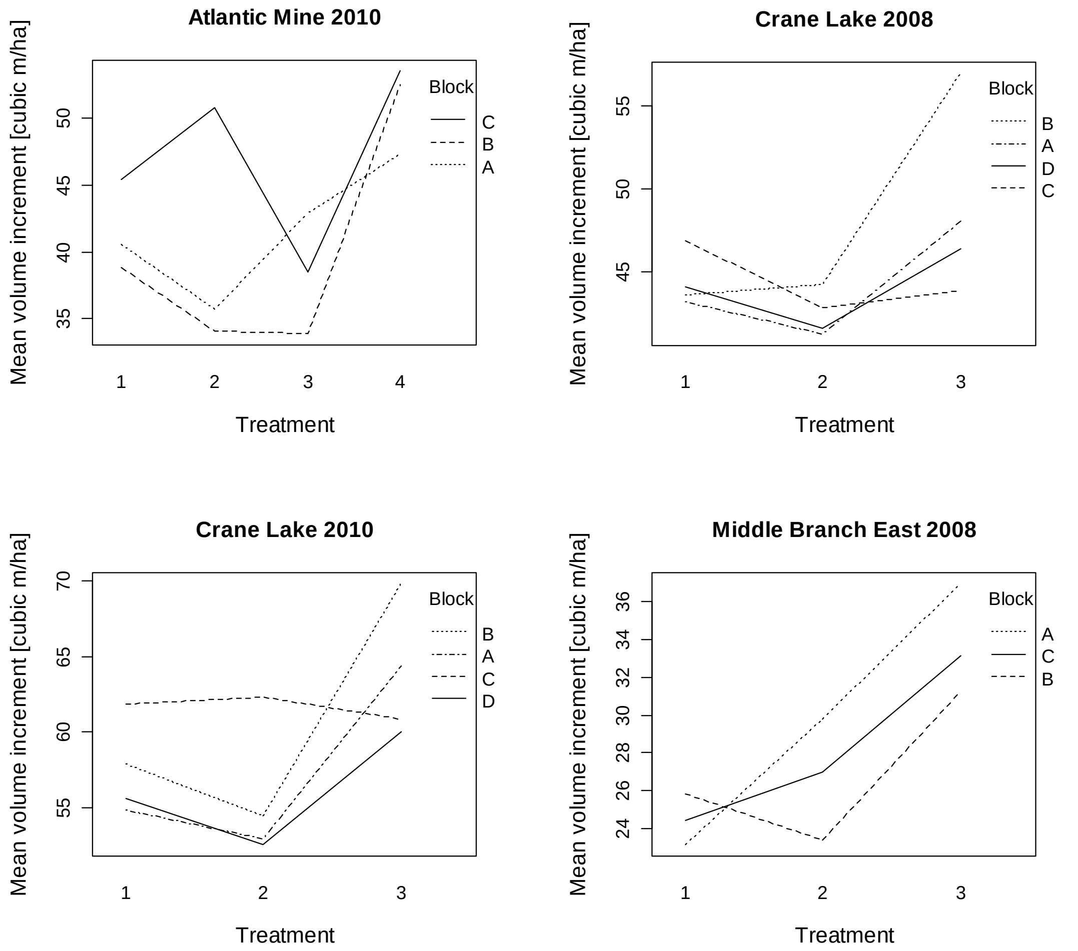

Fig. 9.3 Interaction plots for volume increment

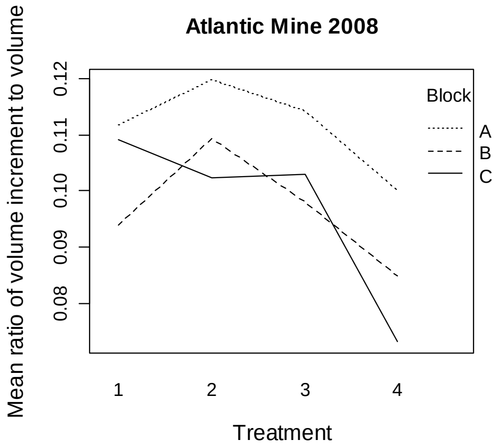

Fig. 9.4 Interaction plot for volume increment to standing volume ratio

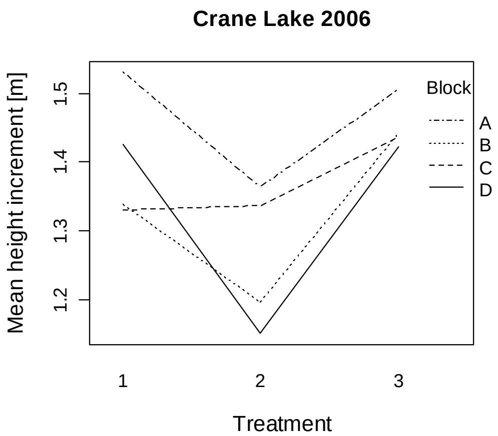

Fig. 9.5 Interaction plots for height increment