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Growth Relationship among Shoot, Branch, Crown and Stand and Disaster Mitigation in Coastal Black Pine Forest

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Abstract: The growth form of coastal black pine (*Pinus thunbergii*) forest, in the coastal city of Fukuoka, was investigated to provide information for disaster mitigation. These forests provide windbreak against high wind and salt spray. In each stand, growth of shoot, branch, crown and the relative light intensity were measured. The largest biomass occurred in current-year shoots (the outer most shoot of a branch) and current-year shoot length was related to the relative light intensity. The current-year shoot biomass, branch biomass and crown biomass were all proportional. The current-year shoot biomass ratio in the lower to upper crowns was related to the crown length ratio and to the mean of relative light intensity from bottom to the top of crown. Crown length ratio became smaller at higher stand density as current-year shoot growth was restricted by neighboring trees. In low-medium density stands, the crown biomass decreased with increasing stand density, but crown biomass increased slightly in high-density stands. As crown length ratio and crown biomass influence the efficacy of disaster mitigation of the forest, the function can be enhanced by adjusting stand density to optimize these crown elements that provide high levels of windbreak.

1 Introduction

Coastal forest in Japan protects adjacent areas from damage by typhoon, coastal erosion, tsunami, strong winds and salt spray (Murai *et al.*, 1992). According to Kawai (1993), the width and length of the forest, as well as the height, density, and orientation, critically influence windbreak performance. However, as it is difficult to change the length and width of forest located in city suburbs in Japan, performance can only be enhanced by changing the internal structure of the forest.

Since black pine (*Pinus thunbergii*) is tolerant to strong wind and salt spray (Jiaojun *et al.*, 2001), this species is widely planted as coastal forest in Japan (Fukuchi, 2001). For coastal forest management, the index of the lowest branch height to tree height ratio (i.e., crown length ratio) and/or tree height to trunk diameter ratio (slenderness ratio) are used to enhance forest wind resistance (Torita and Nemoto, 2002). However, these measures only consider mitigation of damage by strong winds. The amount of salt trapped by a tree is related to the leaf area or leaf biomass (Saito and Imai, 2004), although the extent of salt spray mitigation by black pine leaf is not clear.

Suzuki (2003) showed that the number of current-year shoots and the leaf biomass for branches of some broad leaves trees was proportional to the basal cross-sectional area of the branch. Osada *et al.* (2004) reported the number of leaves and length of the current-year shoot present in the leader crown of beech (*Fagus crenata*) increased with tree height and higher relative light intensity. The length and the number of current-year shoots in silver birch (*Betula pendula*) increased from the bottom to the top of crown and from low to high orders of branches (Vehanen and Kaitaniemi, 2006). No similar measurements have been completed of black pine.

In the present study, biomass, size and age of the shoot, branch, tree crown, stand and the relative light intensity were measured in a coastal black pine forest at various positions in the forest. These measurements were used to estimate the growth of the current year shoot, test the relationship between branch and crown growth and stand density and consider how disaster mitigation function of the forest can be enhanced.

2 Materials and methods

2.1 Study area

Forest stands in two districts, Sawara and Uminonakamichi, located in the coastal city of Fukuoka, Japan (Figure 1), were studied.

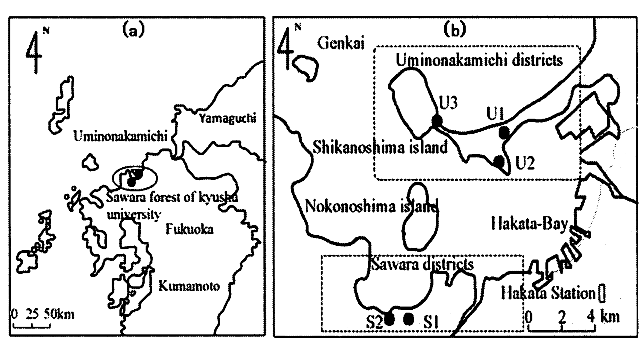

Figure 1: Map of southwestern Japan (a) and the study area (b)

The Sawara study area is located on a sand dune 30 m wide and 1,000 m long (3 ha) parallel to the coastline. The black pine forest of the district is part of national park (20 ha in area) and provides a windbreak for the residential area inland. Two stands (S1 and S2 Figure 1)

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planted in 1991 and 1996 were surveyed.

The Uminonakamichi study area (143 ha) is located on a sand bar in a 540-ha national park. Three stands (U1, U2 and U3 Figure 1) planted in 1987-1989 were surveyed.

Neither forest has been thinned or managed, and dieback of branches can be seen throughout the stands. Each stand was 1,000 m^2 and all stands (S1, S2, U1, U2 and U3) are typical of the district.

The Japan Meteorological Agency (2009) reports the annual mean values of precipitation, air temperature, sunshine hours and wind speed at the Fukuoka District Meteorological Observatory (Figure 1) were 1,632 mm, 16.6°C, 1,849 hours and 2.9 m/s. The highest ever-recorded instantaneous wind speed was 49 m/s. The study area has an elevation of less than 5 m above sea level (Geographical Survey Institute, 2005).

2.2 Measurement of forest stand

In 2007, data were collected from three plots (10 × 10 m) in each stand. In each plot, the number of trees and, for each tree, trunk diameter at breast height (DBH), tree height and the length (vertical length) and width of the crown were measured.

The data for each parameter were averaged within each plot and all three plots were combined to estimate mean values for each forest stand.

Stand crown length to tree height ratio (hereafter crown length ratio) was calculated from values of crown length and tree height from the plots.

2.3 Schematic diagram of shoot growth

Figure 2 is a schematic diagram of growth of black pine, based on our observation at the study area. Black pine branches produce new shoots (current-year shoots) once a year between March and July. The shoot emerges at the top of the previous year's shoot. Shoot growth immediately prior to the current-year shoot is a "one-year old shoot", the shoot growth immediately prior to one-year old shoot is a "two-year old shoot" and so on for all previous years.

Current-year shoots are composed of the main shoot (the longest one) and about five lateral shoots. Leaves only grow on the current-year, one-year-old and two-year-old shoots. Most leaves on two-year old shoots dieback in the third year. The diameter of the shoot increases each year; however, the length of shoot does not change after the first year. At the top of each branch, a new current-year shoot appears once a year on the previous year's shoot.

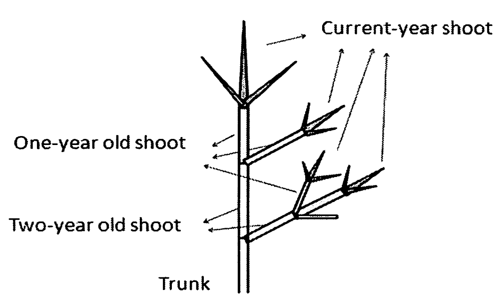

Figure 2: Schematic diagram of growth of black pine trees

Hence, the shoot age becomes older from top to the bottom for each branch and the branch age (i.e., the oldest age of the shoot of branch) becomes older from top to the bottom for a crown.

2.4 Measurement of the relative light intensity

Mesh points were located in a 10-m × 10-m plot at 2-m intervals. Sky photographs were taken at each mesh point with a digital camera equipped with a fish-eye lens, up through the canopy from the bottom of crown to the top of the canopy at intervals of 1 m.

Diffuse skylight was measured from the images using dedicated software (Yahata, 1991). The relative light intensity (or the relative photosynthetic photon flux density) was taken as the ratio of the light intensity inside the forest to outside the forest (open space).

2.5 Measurement of biomass of shoot, branch and crown

Branches were sampled from trees with a DBH close to the mean of the stand. Samples were taken at 1-m height intervals near to each mesh point. Three branches were sampled at each height and the length, bottom diameter and biomass of current-year shoots were measured. Data were collected from five trees in each plot.

The axial volume for main and lateral shoots was taken as axis length × axis diameter for the shoots of each year. Axis dry biomass was estimated from volume × 0.48 (specific dry weight for black pine (David *et al.*, 2007)).

The number of leaves growing on a 10-cm-long section of current-year, one-year-old and two-year-old shoots was counted for all branches sampled to calculate mean number of leaves per centimeter on each age shoot. All sampled leaves were oven-dried, weighed and the mean leaf weight was calculated.

The shoot biomass was taken as leaf biomass plus axis biomass for current-year and two-year-old shoots; axis biomass was shoots older than 3 years. Branch biomass was the biomass of all shoots comprising a branch. Crown biomass was the biomass of all branches in a crown.

Table 1: Density and average tree height, diameter at breast height (DBH) and tree age for each stand

Parameter	S1	S2	U1	U2	U3
Stand density (trees/ha)	1,200	5,900	1,500	2,000	2,900
Tree height (m)	5.7	8.1	8.6	8.4	8.3
Diameter at breast height (DBH) (mm)	121	63	119	103	89
Tree age (years)	12	17	20	20	18

Table 2: Shoot biomass (kg/tree) according to shoot age for the upper and lower crowns in each stand

Stand	Upper/Lower Cr. (Crown)	Shoot age (years)												
		Current year	1	2	3	4	5	6	7	8	9	10	11	12
S1	Upper Cr.	5.63	5.13	4.49	2.83	2.16	1.97							
	Lower Cr.	2.41	2.46	3.03	2.50	1.61	0.88	0.46	0.24	0.10	0.02			
S2	Upper Cr.	0.99	0.92	0.79	0.46	0.36	0.33	0.25						
	Lower Cr.	0.24	0.18	0.20	0.22	0.27	0.13	0.07	0.06	0.06	0.04	0.03	0.01	
U1	Upper Cr.	3.99	3.56	2.57	1.27	1.05	0.95	0.93	0.72					
	Lower Cr.	1.55	1.51	1.16	0.71	0.57	0.80	1.04	0.75	0.29	0.14	0.08	0.04	0.01
U2	Upper Cr.	2.30	2.13	1.82	1.03	0.79	0.78	0.64	0.57					
	Lower Cr.	0.74	0.71	0.67	0.40	0.33	0.29	0.48	0.28	0.15	0.11	0.08	0.05	0.01
U3	Upper Cr.	1.82	1.67	1.49	0.74	0.62	0.60	0.48						
	Lower Cr.	0.51	0.52	0.56	0.35	0.22	0.18	0.09	0.07	0.06	0.04	0.03	0.01	

Biomasses of shoot, branch and crown were divided into upper and lower halves by height. The crown biomass of a stand was derived by the mean crown biomass × number of trees in the stand.

3 Results

3.1 Characteristics of the forest stand

In S1, the stand density was 1,200 trees/ha, tree height was 5.7 m, and DBH (121 mm) was larger than in the other stands, but the trees were younger (12 years) (Table 1). The highest density was 5,900 trees/ha in S2. In S2, tree height was 8.1 m, but mean DBH (63 mm) was smaller than in other stands.

In U1, U2 and U3 stands, the stand density was 1,500 - 2,900 trees/ha, tree height was 8.3 - 8.6 m, and DBH was 89 - 119 mm. DBH tended to be larger at lower stand densities (Table 1).

3.2 Age and biomass of shoot in the upper and lower crowns

In all stands, branches in upper crowns comprised current-year to 7-year-old shoots and lower crowns comprised current-year to 12-year-old shoots (Table 2). The maximum shoot age of the trees observed in the lower crown was less than the tree age in each stand. Older branches, which had the shoots older than the current maximum shoot age, had died back.

Shoot biomass was the largest for current-year shoots in both upper and lower crowns in each stand, except for the lower crown in S1 stand. The current-year shoot for combined upper and lower crowns biomass was largest in S1 stand, followed by U1 and U2 stands and smallest in S2 stand in both upper and lower crowns.

3.3 Correlation between height above ground level, relative light intensity and length and biomass of current-year shoots

There was a significant correlation between the relative light intensity and current-year shoot length for all stands (Table 3).

There was a significant correlation between height above ground level and relative light intensity for S1, U1, U2 and U3 stands, between height above ground level and current-year shoot length for U1, U2 and U3 stands and between height above ground level and current-year shoot biomass for S1 stand. There was no correlation

Table 3: Correlation coefficients between height above ground level, relative light intensity, length and biomass of current-year shoots at a position in the stand

Parameter	Height above ground level	Relative light intensity	Current-year shoot biomass
Relative light intensity	0.81*-0.95* (S1,U1-U3) 0.73(S2)		
Current-year shoot biomass	0.89*(S1) 0.73-0.92 (S2,U1-U3)	0.53-0.71 (S1-S2, U1-U3)	
Current-year shoot length	0.66-0.81(S1,S2) 0.74*-0.75* (U1-U3)	0.92*(S1) 0.97**-0.99** (S2,U1-U3)	0.36-0.52 (S1-S2, U1-U3)

*: significant at 5% level; **: significant at 1% level.
Letters in the parentheses indicate the names of forest stands.

between relative light intensity and current-year shoot biomass or between biomass and length of current-year shoots in any stand.

3.4 Relationship between biomass and current-year shoots and branches

In the lower crown of a tree, the current-year shoot biomass was 15 - 28 g and branch biomass was 236 - 703 g for the lower crown and the corresponding biomasses for the upper crown were 17 - 31 g and 262 - 777 g (Figure 3). The current-year shoot biomass was proportional to the branch biomass and the proportional relationship was similar in upper and lower crowns.

For each stand, current-year shoot and branch biomasses were smaller in lower than in upper crowns, indicating that current-year shoots and branches grew less in the lower than the upper crowns.

3.5 Relationship of relative light intensity and crown length ratio to current-year shoot biomass ratio in the lower and upper crowns

There was positive linear relationship between relative light intensity and current-year shoot biomass ratio in the lower to upper crowns in all stands (Figure 4 (a)). Current-year shoot biomass ratio was smaller in the lower crown and ranged from 0.24 to 0.43 at relative light intensity of 34 - 43%.

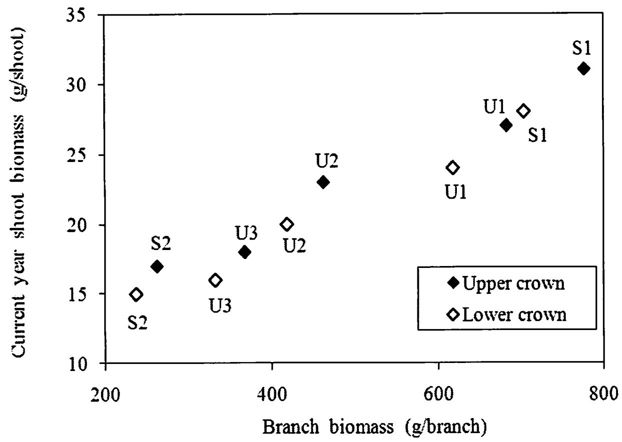

Figure 3: Relationship between branch biomass and current-year shoot biomass for the lower to upper crowns

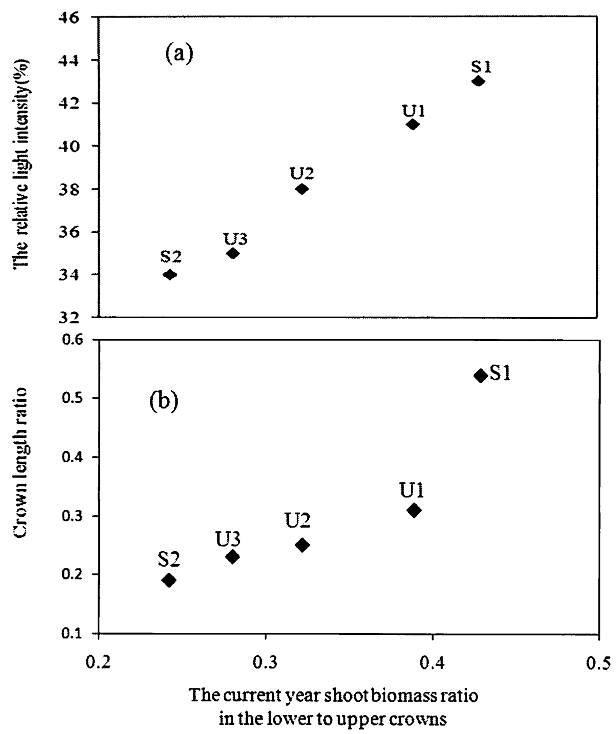

Figure 4: Relationship between current-year shoot biomass ratio in the lower to upper crowns and (a) relative light intensity and (b) crown length ratio

There was a relationship between the current-year shoot biomass ratio in the lower to upper crowns and the crown length ratio (Figure 4 (b)). The smallest current-year shoot biomass ratio, 0.24, occurred in S2 stand when the crown length ratio was 0.19 and current-year shoot biomass ratio was 0.39 as crown length ratio increased to 0.31 in U3, U2 and U1 stands. The current-year shoot biomass ratio in S1 stand was slightly larger than in U1, although the crown length ratio in S1, 0.54, was larger than in U1.

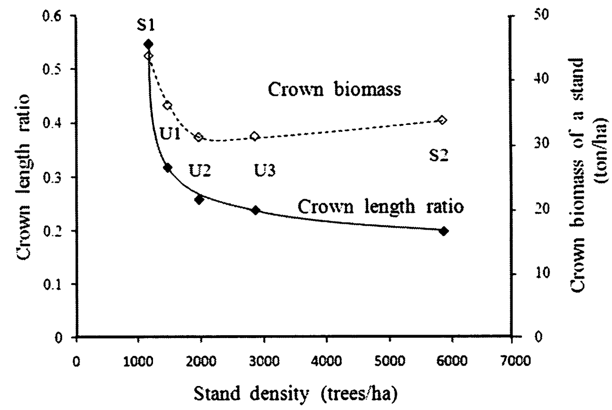

Figure 5: Relationships between crown length ratio and crown biomass of a stand and stand density

3.6 Relationship of crown length ratio and crown biomass with stand density

The crown length ratio decreased from 0.54 to 0.23 as stand density increased from 1,200 to 2,900 trees/ha (S1 and U3 stands) and fell to 0.19 at a stand density 5,900 trees/ha (S2 stand) (Figure 5).

The crown biomass decreased from 43.1 to 35.5 ton/ha as stand density increased from 1,200 to 1,500 trees/ha (S1 and U1 stands) and was lowest at 30.6 ton/ha at 2,000 trees/ha (U2 stand). Crown biomass increased to 33.1 ton/ha at 5,900 trees/ha in S2 stand.

4 Discussion

4.1 Factors affecting shoot growth

The significant correlation between the relative light intensity and current-year shoot length (Table 3) implies that current-year shoots grow more in increased light. However, this does not produce an increase in biomass of current-year shoots. This is the result of the transportation of photosynthetic products produced by current-year, one-year-old and two-year-old leaves to older branches. Branches of all ages continue to grow irrespective of leaves.

The stand density in S2 was very high, and tangle of crown vegetation restricted penetration of sunlight deep into the canopy. The insignificant correlation between height above ground and current-year shoot length observed in S2 stand is explained by restriction of light penetration by the dense canopy. In stands U1, U2 and U3 there was significant correlation between the height above ground level and current-year shoot length. Current-year shoot length in S1 was not significantly correlated with height above ground level, possibly due to the tree age and/or tree height.

In S1, current-year shoot biomass was significantly correlated (Table 3) with height above ground, as lower branches were shaded. In other stands at lower density, current-year shoots did not contact neighboring tree branches and the growth of the biomass was not restricted.

4.2 Factors affecting growth of shoots, branches, crown and forest stand

At higher density stands, higher crowns shade the lower crown. If the current-year shoot growth in the lower crown is restricted, branches will die back in the future. Dieback of lower crown branches will lower crown length ratio. Figure 4 (b) shows that the crown length ratio was positively related to the current-year shoot biomass ratio in the lower to upper crowns, which could have been caused by branch dieback in the lower crown.

Current-year shoot biomass and branch biomass were smaller for the lower crown than for the upper crown (Figure 3) and stand density had a negative effect on the crown length ratio. Both changes are related to dieback of lower crown branches. Since the crown biomass decreased initially and then increased as the stand density increased (Figure 5), the crown biomass can be manipulated by changing stand density.

The current-year shoot biomass of a branch was related to the branch biomass (Figure 3) and the current-year shoot biomass ratio in the lower to upper crowns was related to the crown length ratio (Figure 4(b)). The crown length ratio and crown biomass of a stand were also correlated to stand density (Figure 5). The growth of current-year shoots is dependent on the growth of branches, the crown and stand density.

This finding indicates that dieback of current-year shoots and branches controls the growth form of black pine.

4.3 Improved forest structure for disaster mitigation

In black pine plantations, larger crown length and slenderness ratio help prevent wind damage (Taoda, 1988).

As both ratios are positively related by our own analysis, crown length ratio can be used as an index of wind resistance in place of slenderness ratio. Higher ratios mitigate wind damage (Kaneko and Tamura, 2002).

Black pine leaves trap salt spray (Matsuoka and Eto, 1987) and a higher leaf biomass will mitigate salt damage. As the crown length ratio and crown biomass become larger at lower stand densities, stand density can be manipulated to achieve maximum values.

Forest management should aim to maximize leaf biomass and crown length ratio, both of which are high at a stand density of less than 2,000 trees/ha. Although a stand density of 6,000 trees/ha produces a higher crown biomass, the crown length ratio is reduced.

For a high function of disaster mitigation, the stand density should be less than 2,000 trees/ha, and for that, restructuring of the forest by thinning of the trees will be necessary in medium-high density stands .

5 Conclusions

Stand density affects key growth form characters in black pine plantations. As growth form affect the efficacy of windbreak for black pine, changing the stand density will enhance mitigation of high wind and salt spray. A stand density of less than 2,000 trees per ha will produce optimal growth form.

The present study found the highest biomass in current-year shoot. The current-year shoot length was related to the relative light intensity in the forest and shoots grew longer in response to higher light intensity. Shoots were older in the lower than in upper crown but younger than tree age. Older branches, which had the shoots older than the current maximum shoot age, had died back.

Current-year shoot biomass was proportional to the branch biomass. In addition, the current-year shoot biomass ratio in the lower to upper crowns was related to the crown length ratio and to the relative light intensity. The higher the stand density, the smaller the crown length ratio. Growth of current-year shoots was restricted by the proximity to neighboring trees. Crown biomass decreased with increased stand density in low-medium density stands, but increased slightly in high density stands.

Growth of current-year shoots was related to the growth of crown biomass and crown length ratio at the stand affected by the stand density. Since the crown biomass and the crown length ratio are linked to disaster mitigation of forests, restructuring forests to optimize these factors may enhance forest functions.

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