Implication of Self-thinning in *Salix* Communities on Riverine Wetland Restoration

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ABSTRACT: Self-thinning was measured in *Salix* communities on Bam Island in Seoul at various age stages. D^2H was used to estimate tree biomass, where D is stem diameter at breast height or 10 cm height for plants with height <1.5 m, and H is height. A log-log plot of density versus D^2H and correlation analysis indicated a significant relationship between density and biomass with equation 'log D^2H = −1.27 log N + 7.06'. This indicates that self-thinning affects biomass in the *Salix* community with −1.27 as the thinning coefficient. If we assume a thinning exponent −3/2, then the allometric coefficient of the equation, log w = a log D^2H + b, is 1.18. This is much higher than that for any other species studied in Korea. There were statistically significant relationships between age and density and between age and basal area and these relationships suggest guidelines for transplantation of willows and for the assessment of *Salix* community restoration projects in riverine wetlands based on standard density, basal area, and age. The results of this study may also increase understanding of succession processes in *Salix* community restoration in riverine wetlands.

Key words: Allometric equation, Assessment of restoration project, Bam Island in Seoul, −3/2 power rule

INTRODUCTION

The self-thinning rule, also known as the −3/2 power law, describes the rate at which plants die because of competition in crowded even-aged stands with a closed canopy as a function of the rate at which biomass accumulates (Yoda et al. 1963). This rule assumes that mass per shoot will be proportional to the cube of the linear dimension and can be extended to monospecific stands of single-stemmed plants ranging in size from mosses to trees despite major differences in plant architecture and the nature of supporting tissues (Gorham 1979). The self-thinning rule is represented by the equation $w = cN^{-3/2}$ or equivalently $B = wN = cN^{-1/2}$, where w is the mean mass of surviving plants, N is the density of survivors, B is biomass per unit area, and c is a constant. This equation produces a straight line of slope −3/2 in a space of log mean mass against log density or of slope −1/2 in a space of log biomass against log density.

Even though there is still controversy about whether this rule is true (Lonsdale 1990), the self-thinning rule has important scientific implications (Westoby 1981) and potential applications to conservation and restoration of plant populations, such as selection of plant size and density in restoration projects.

Salix seeds germinate on wet mineral soils under a very narrow range of water and light conditions. However, when these condi-

tions are satisfied, germination rates are very high, up to 250 seeds m^{-2} (unpublished data). Because it is difficult to achieve appropriate germination conditions in riverine restoration projects, young shoots or live branches of *Salix* plants are generally planted on the marginal slopes to prevent soil erosion (Kim and Lee 1998a, 1998b, 1999, Lee and Lyu 2003). However, there are few data about the relationship between planting density and succession (Koo et al. 2002) and no data by which to judge the success of restoration projects. Because the survival and reproductive success of individual plants is better predicted from their size than from their chronological age (Werner 1975), density and size data are required for judging success or failure of the restoration project.

In this study, we used density and size (stem diameter and height) data to assess whether there is self-thinning in pure stands of *Salix*. This is an easier method for detecting the self-thinning process than previous methods which require the use of destructive mass data and provides the same information about the self-thinning process. Here, we employ age, density and basal area plots to understand changes in *Salix* tree characteristics with time in pure stands of *Salix* in riverine wetlands. The results can be used in the formulation of guidelines for *Salix* community restoration and assessment.

STUDY SITE

Bam Island is located in central Seoul, Korea, and was desig-

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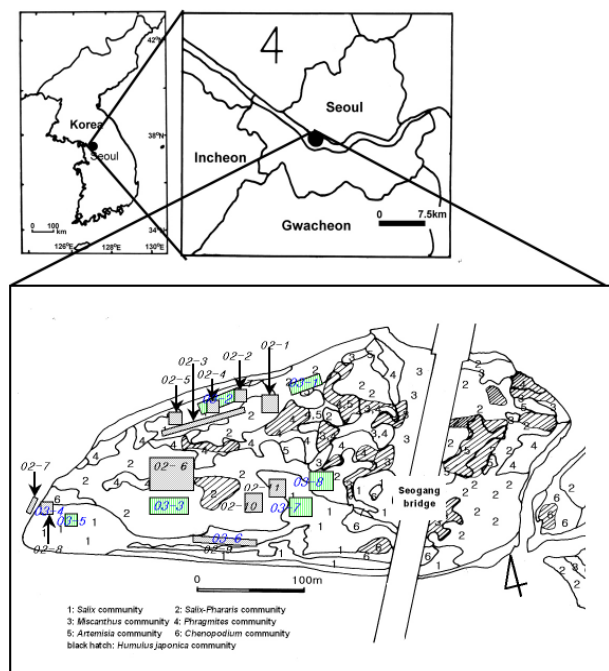
Fig. 1. Sampling sites on lower Bam Island in Seoul. Sites 02-x were sampled in 2002 and 03-x were sampled in 2003.
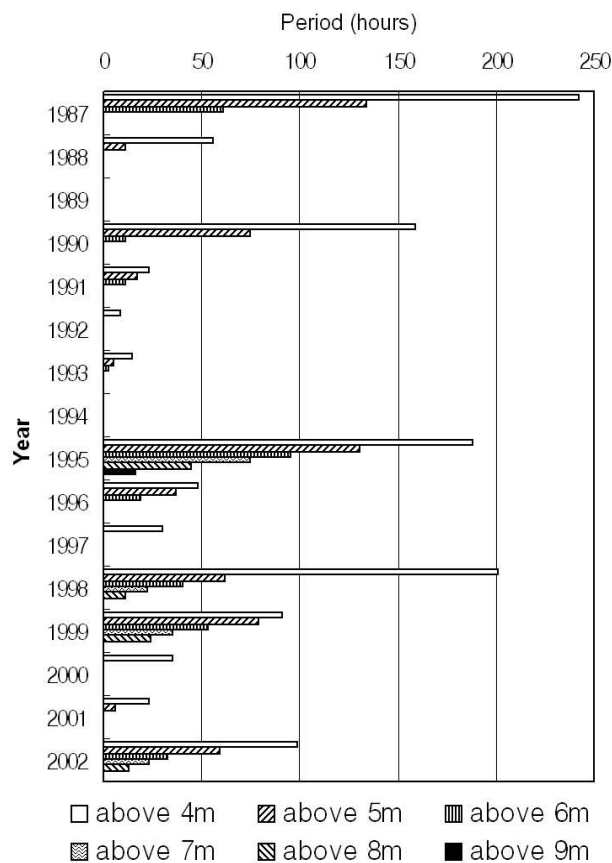

Fig. 2. Water level of the Han River at the Han Bridge. Bam Island begins flooding at a water level of 4 m and all willow trees are submerged at 9 m. The flooding level is also related to the increases in the size of Bam Island. Data from Water Management Resources Information System http://www.wamis.go.kr/

nated as a nature conservation area in 1999 (Fig. 1). Bam Island was badly damaged in 1968 by the removal of rocks and soil for the construction of the Yeoui-do residential and commercial area. However, in the past few decades there has been additional deposition and settling of sediments, and the island has grown. Bam Island reached its present shape in 1986 with the completion of the development of the Han River (Seoul Metropolitan City 2004). Bam Island is flooded every year to a level determined by the water level of the Han River (Fig. 2). Bam Island was flooded entirely in 1996, 1998, and 2002, and sediment accumulation rate was high in these years (Han and Kim 2006). Increases in island size have been closely related to flooding level (Seoul Metropolitan City 2004), and the size of Bam Island increased from 0.18 km^2 in 1985 to 0.25 km^2 in 2002. Dominant plant species on Bam Island are *Salix koreensis*, *Phragmites communis*, *Phalaris arundinaceae*, *Miscanthus saccariflorus* and *Humulus japonica* (Seoul Metropolitan City 2004). Pure *Salix* stands have formed on the edge of the island with the expansion of island size. There are several *Salix* stands of equal age on Bam Island with closed canopies.

METHODS

We could not use destructive methods to measure biomass because Bam Island is a nature conservation area. However, the thinning exponent in the self-thinning rule should be systematically related to the exponents of allometric equations relating to average height and average mass, average height and average stem diameter (D), and average height and average basal area (Weller 1987). Stem diameter, tree height and tree density were measured in 11 quadrats on Bam Island in March 8, 2002 and 8 additional quadrats on March 16, 2003 (Fig. 1). Basal area was calculated from the stem diameter (Kim et al. 2004). Quadrats sizes were 1 m × 1 m for pure *Salix* stands of age 1 to 2 years, 5 m × 5 m or 3 m × 7 m for stands of age 3 to 7 years, 10 m × 10 m or 20 m × 5 m for stands of age 7 to 15 years, and 25 m × 25 m for stands of age 15 to 24 years. Quadrats were rectangular or square in shape. Different quadrat sizes was employed for the same age classes because some *Salix* communities were distributed in strips of width < 5 m or <10 m. Stem diameter was measured at breast height for trees taller than 1.5 m and was measured with micrometer calipers at 10 cm height for trees shorter than 1.5 m. All willow trees in the quadrats were 1~24 years old based on tree-ring data and annual aerial photo-

graphs of Bam Island. Densities were calculated from the number of *Salix* trees per m^2.

RESULTS AND DISCUSSION

Self-thinning in *Salix* Communities

A log-log plot of density and D^2H approximates a straight line of slope −1.27, indicating density-dependant mortality (Fig. 3). Lonsdale and Watkinson (1983) argue that the −3/2 power rule applies to the volume of canopy available for plants rather than their mass, and that some of the observed variation in gradients of mass-density thinning lines may be due to variation in the relationship between biomass per unit volume of canopy (B/V) and canopy height. So, tree biomass was recalculated with the equation, tree biomass = 0.5 × basal area × tree height (Whittaker and Marks 1975), resulting in a log-log plot of density vs. average biomass with the identical slope (−1.27).

Lonsdale (1990) suggested that the slope may shift to −1 as the population reaches maximum yield or as effects of resource availability become pronounced. The slope has been generally thought to lie between −1.3 and −1.8, but with an ideal value of −1.5 (White 1985). Nutrient levels are very high in Bam Island because of the high organic input produced by annual flooding (Seoul Metropolitan City 2004). Accordingly, plants can grow without nutrient limitation, and yields of plants might approach the maximum possible given local climatic conditions. Therefore, the slope of the log-log plot of density vs. D^2H for *Salix* communities in the study area should be between those predicted by the −3/2 power rule and maximum yield, and may deviate from the self-thinning rule of Yoda et al. (1963). In general, natural *Salix* communities are formed on alluvial soil in riverine wetlands like Bam Island, and nutrient levels in these regions is generally high (Mitsch and Gosselink 2000). These results suggest that *Salix* communities follow the self-thinning rule.

There may be a number of reasons for deviation from a slope of −1.5 in allometric characteristics of *Salix* trees. Most environmental factors such as soil fertility affect the rate of accumulation of biomass but not the trajectory followed on the B-N diagram (Yoda et al. 1963, White and Harper 1970). Variation among species will occur in the position of the thinning line on a mass plot because of differences in B/V values resulting from differences in leaf geometry, branching patterns, and wood densities (Lonsdale 1990). Therefore, many studies have tried to find allometric relationship between biomass and volume (Hozumi 1963, Kira and Shidei 1967, Kim 1970, Kim 1971, Kim and Yoon 1972, National Institute for Disaster Prevention 2001).

The general allometric equation is "log w = a log D^2H + b" where 'w' is average tree mass, 'D' is average stem diameter, 'H' is average tree height, and 'a' and 'b' are constants. If we assume that the thinning exponent of *Salix* communities is −3/2 in a log-log plot of density and biomass, the difference between the observed thinning coefficient of −1.27 (Fig. 3) and the −3/2 coefficient predicted by the power rule might result from the allometric characteristics that were used to calculate biomass from the diameter and height.

The regression equation from Fig. 3 is:

$$\log (D^2H) = -1.27 \log (\text{Density m}^{-2}) + 7.06 \qquad ①$$

Whereas the −3/2 power rule can be expressed as follows:

$$\log w = -3/2 \log N + c \qquad ②$$

where w is average tree mass, N is tree density (m^{-2}), and c is a constant.

The allometric equation used to calculate biomass was:

$$\log w = a \log D^2H + b \qquad ③$$

where a and b are constants.

The term "log w" of equations ② and ③ is the same, which means that:

$$a \log D^2H + b = -3/2 \log N + c \qquad ④$$

and from equations ① and ④,

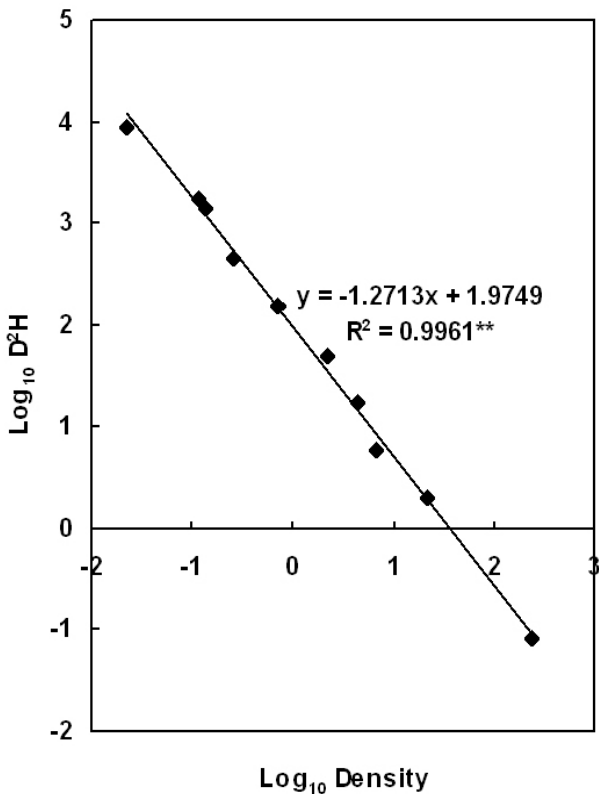$$-1.27 \ a \log N + 7.06 \ a + b = -3/2 \log N + c$$

Therefore, $a = 1.18$

Fig. 3. Log-log diagram of density and D^2H of *Salix* trees showing the self-thinning rule.

y = -1.2713x + 1.9749
R^2 = 0.9961**

Twenty tree species were modeled with allometric equation ③ in Korea and values of the resulting allometric coefficients (*a*) were between 0.579 (*Quercus mongolica*) and 0.992 (*Rhododendron mucronulatum* var. *ciliatum*) (Kim 1971, Kim and Yoon 1972, National Institute for Disaster Prevention 2001). Accordingly, the value 1.18 calculated for *Salix* spp. in this study is much higher than allometric coefficients calculated for other species in Korea, which suggests that *Salix* spp. have more branches and leaves than do most other species.

Even though Weller (1987) suggested that thinning exponents can deviate more widely from −3/2 than previously thought, it is not certain whether the actual thinning exponent for *Salix* spp. is −3/2 or −1.27 because there are no data that can be used to verify the allometric relationship between tree biomass and tree volume expressed as D^2H. To reveal the exact thinning exponent, destructive measuring methods must be used to establish the appropriate allometric equation. However, the results of this study confirm that there is self-thinning process in natural *Salix* communities in Bam Island.

Implication of the Self-thinning Process for *Salix* Community Restoration in Riverine Wetlands

Even though *Salix* spp. including *S. gracilistyla* have been transplanted as a part of many riverine wetland restoration projects in Korea, there have been no reports about changes in *Salix* community characteristics over time in assessments of these projects. Most knowledge about willow restoration has been developed from the experience of practitioners. Practitioners transplant young willow trees or branch cuttings at 0.5 m, 1 m or 2 m intervals based on their experiences. The transplanted willows then produce many branches which fill the remaining open area in a few years, after which some branches or trees die (personnel observation). In this case, the death of some plants is the result of a natural self-thinning phenomenon, which results in inefficient use of practitioners' resources in restored habitats.

Fig. 4 shows the relationships between age and density, and age and basal area. It is necessary to know the density and basal area of a willow population at a given age to determine whether the population is undergoing a natural successional process, because the state of a plant population cannot be satisfactorily described by its biomass or by the number of individuals it contains alone (Harper 1977, White 1980). The number of *Salix* trees in a natural community decreases sharply with age, and other plants do not grow on the community floor until the *Salix* stand reaches 5~6 years of age. However, it is almost impossible to transplant young willow trees or branch cuttings at natural densities (Fig. 4). This means that herbs will be able to grow under young *Salix* trees and these herbs com-
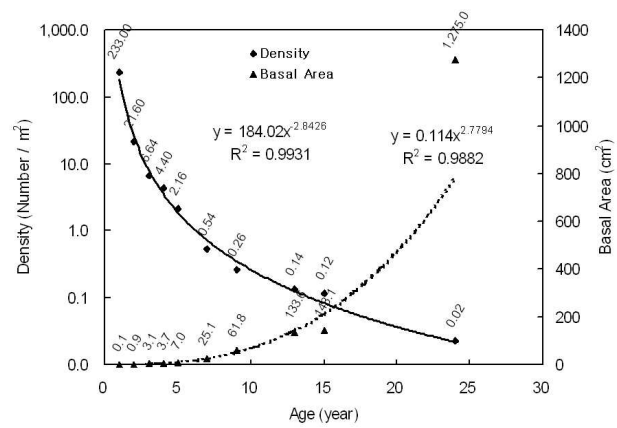

Fig. 4. Relationships between age and density (straight line, logarithmic scale) and between age and basal area (dotted line) in *Salix* communities.

pete with *Salix* trees for nutrients and light.

The results of our study suggest that willow transplantation methods used in previous projects were inadequate to ensure that most transplants survive without management. There are two possible methods for reliable willow restoration in riverine wetlands: one is to transplant an adequate number of willow cuttings and the other is to manage environments to allow willow seeds to germinate. The second method is much more complex and difficult than the first. Unless the practitioners are able to transplant a natural density of willow cuttings (21 cuts per m^2) as suggested in this study, the best way to maximize willow survivorship is to manage the growth of herbs on the forest floor until the willows grow sufficiently to close the canopy. Fig. 4 provides a guideline that can be used to assess the progress of the restoration project over time based on the relationship between age and basal area (or D^2H) or between age and density.

CONCLUSIONS

Based on the log-log plot of D^2H and density of *Salix* trees, we found a self-thinning process in pure *Salix* communities, but the thinning coefficient was different from that predicted by the −3/2 power rule. This might result from the intrinsic characteristics of *Salix* trees or a result of the allometric characteristics of *Salix*. The allometric coefficient of log *w* = *a* log D^2H + *b* was 1.18, which was much higher than those of 20 other tree species studied in Korea. The age and density and age and basal area plots suggests a guideline for transplantation of willow cuttings for *Salix* community restoration in riverine wetlands, and can also be used to assess restoration project based on stem diameter, height and density. This study may improve the understanding of succession processes of

Salix communities in riverine wetland.

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