Root Restriction Effects on Growth and Development of *Salvia (Salvia splendens)*

Marc van Iersel

Department of Horticulture, Georgia Station, University of Georgia, Griffin, GA 30223

Additional index words. container volume, growth analysis, relative growth rate, net assimilation rate, leaf area ratio, flowering

Abstract. Container size can affect the growth and development of bedding plants. The effects of widely differing container sizes on growth and development of salvia (*Salvia splendens* F. Sellow ex Roem. & Schult.) were quantified. Plants were grown in a greenhouse in 7.3-, 55-, 166-, and 510-mL containers. Container volume affected plant growth as early as 18 days after planting. Growth was positively correlated with pot size and differences increased throughout most of the growing period. Growth of the plants in the 7.3-mL cells was reduced because of a low net assimilation rate ($4.34 \text{ g}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$), compared to the plants in the 55-, 166-, and 510-mL pots ($\approx 5.44 \text{ g}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$). Plants in 510-mL containers grew faster than those in 55- and 166-mL containers because of a higher leaf area ratio. Both lateral branching and leaf expansion were suppressed by root restriction and flowering was delayed. The growth rate of plants in 166-mL pots declined after the onset of flowering, and final plant size was comparable for plants in 55- and 166-mL pots. Although water deficit stress or nutrient deficiencies cannot be excluded as contributing factors, these were probably not the main reason for observed differences.

Greenhouse crops are grown in many types of containers, with volumes that vary widely. Since container volume affects the amount of available water and nutrients, it can have pronounced effects on growth of plants. Most research on effects of container volume on growth and development has focused on vegetables (Bar-Tal et al., 1995; Carmi and Heuer, 1981; NeSmith, 1993; Peterson et al., 1991a, 1991b, 1991c), woody ornamentals (Dubik et al., 1989, 1990; Tilt et al., 1987) and trees (Hanson et al., 1987; Ismail and Noor, 1996). This research shows that root restriction can decrease both root and shoot growth of plants. Processes suggested to be involved in this growth reduction include inhibition of leaf elongation (Peterson et al., 1991b), photosynthesis (Ismail and Noor, 1996; NeSmith, 1993), changes in dry matter partitioning within the plant, nutrient uptake (Bar-Tal and Pressman, 1996; Dubik et al., 1990), and hormone metabolism (Carmi and Heuer, 1981; Peterson et al., 1991a, 1991c). Pretransplant root restriction often decreases early yield of vegetables, while effects on total yield are usually less pronounced (Marsh and Paul, 1988; Maynard et al., 1996; Waters et al., 1990; Weston, 1988; Weston and Zandstra, 1986).

Although container volume can obviously affect the growth of plants, little research has

been done on the effect of cell size on the growth and development of ornamental bedding plants. Latimer (1991) studied the effect of container size and shape on the landscape performance of marigold (*Tagetes erecta* L.). Leaf area and shoot dry mass of marigold seedlings were positively correlated with container volume, while effects on plant height were minimal. Although posttransplant growth of plants from small containers was more rapid than that of plants from larger containers, final size was reduced. Landscape performance of marigold was reduced by root restriction, and these effects appeared to be larger than those previously reported for vegetable transplants (Latimer, 1991).

There appear to be no published reports that focus on the effects of pot size on the growth of ornamental bedding plants during greenhouse production. The objective of this study was to quantify the effects of container volume on the growth and development of salvia, a popular bedding plant. Leaf area ratio (LAR), net assimilation rate (NAR), and relative growth rate (RGR) were determined to help explain observed differences.

Materials and Methods

Plant material. *Salvia* seeds (cv. Top Burgundy) were planted in containers of several sizes on 2 Feb. 1996. Containers were filled with a peat-lite growing medium (Metro-Mix 300; Grace Horticultural Products, Cambridge, Mass.; initial pH = 6.1, EC = $3.4 \text{ dS}\cdot\text{m}^{-1}$ as determined by the pour-through method) and covered with clear polyethylene film for the first 10 d after planting (DAP) to improve germination. Plants were thinned to one plant per pot shortly after germination. The pot sizes

used were (mL per plant): 7.3 (plug flat, 288 shallow cells per flat), 55 (72 cells per flat), 166 (32 cells per flat), and 510 ($10 \times 10\text{-cm}^2$ containers). The shape of these containers was similar, with square tops tapering off to the bottom. Flats were placed on a moist capillary mat to prevent the growing mix from drying out. To deter the roots from growing into the mat, plants were moved regularly. Plants were spaced widely to minimize interplant competition for light and watered overhead once or twice daily as needed. Plants were fertilized twice weekly with a 20N-4.4P-16.6K water-soluble fertilizer ($200 \text{ mg}\cdot\text{L}^{-1}$ N, 20-10-20 Peat-Lite special; The Scotts Co., Marysville, Ohio). Fertilization was started after the appearance of the first true leaf.

Measurements. Four plants were harvested from each experimental unit at weekly intervals, starting at 18 DAP. Leaf area was measured with a leaf area meter (LI-COR 3000A; LI-COR, Lincoln, Nebr.). After washing the growing medium from the roots and drying the samples at 70°C for at least 3 d, root and shoot dry mass (DM) were determined. Second order polynomial functions were fitted to the data according to:

$$\ln(X) = a + b_0 \times t + b_1 \times t^2 \quad [1]$$

where X = variable of interest (plant DM, shoot DM, root DM, or leaf area), t = time (days) and a , b_0 , and b_1 are regression parameters. This function fit the data well in all cases ($r^2 > 0.98$). Relative growth rate (RGR, d^{-1}) was calculated as the first derivative of this function (Hunt, 1982):

$$\text{RGR} = b_0 + 2 \times b_1 \times t \quad [2]$$

and net assimilation rate (NAR, $\text{g}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$) as:

$$\text{NAR} = \text{RGR} \times M_t/A_t \quad [3]$$

where M_t and A_t are whole plant DM and leaf area at time t , respectively. Leaf area ratio (LAR, $\text{m}^2\cdot\text{kg}^{-1}$) was determined as total leaf area per plant DM. The number of flowering plants was determined every other day from 53 until 67 DAP. Plants were considered to be flowering when the flower bud was $>1 \text{ cm}$ in diameter.

The experimental design was a randomized complete block with four replications and repeated sampling over time. All dry mass and leaf area data were transformed according to $\log(x+1)$ to stabilize the variance before analysis of variance. Because of significant interactions between container volume and plant age for shoot and root DM and for leaf area, these data were further analyzed separately for the different harvest times. When this interaction was not significant (NAR, LAR), data were pooled over plant age to emphasize differences between container volumes. Mean separation was conducted on the transformed data, but the original data are presented as mean values per plant.

Results and Discussion

Cell volume affected dry mass accumulation (Fig. 1, Table 1) and leaf area development (Fig. 2) of salvia from the early stages of

Received for publication 9 Dec. 1996. Accepted for publication 11 Apr. 1997. I thank Scott NeSmith, John Ruter, and Paul Thomas for their helpful comments and Jerry Davis for his help with the statistical analysis. The cost of publishing this paper was defrayed in part by the payment of page charges. Under postal regulations, this paper therefore must be hereby marked advertisement solely to indicate this fact.

Fig. 1. The effect of container volume on shoot (A) and root (B) dry mass of salvia (container volume: ∇ 7.3 mL, $\blacktriangledown$ 55 mL, $\circ$ 166 mL, and $\bullet$ 510 mL). Mean separation within days by Fisher's protected LSD_{0.05}.

Table 1. Net assimilation rate (NAR), leaf area ratio (LAR), shoot and root dry mass, and shoot : root ratio of *Salvia splendens* as affected by container volume. Data for NAR and LAR represent the mean values from 18 to 67 d after planting.

Container volume (mL)	NAR (g·m ⁻² ·d ⁻¹)	LAR (m ² ·kg ⁻¹)	Final dry mass (g)		Shoot : root ratio
			Shoot	Root	
7.3	4.66	26.7	0.57	0.13	4.60
55	6.14	22.1	1.27	0.46	2.89
166	6.00	22.8	1.35	0.71	1.91
510	6.06	24.5	3.89	1.20	3.24
Significance	Q*	Q*	L***	L***	Q**

*, **, *** Significant at $P \leq 0.05$, 0.001, and 0.0001, respectively [linear (L) or quadratic (Q) effects of container volume].

development. A small root zone inhibited both root and shoot growth as early as 18 DAP (≈ 9 d after emergence) and differences increased rapidly during the first 46 d of the experiment. Shoot growth of the plants in 166-mL containers slowed simultaneously with the onset of flowering. The plants in these containers had little lateral growth, while terminal growth was reduced by the flowering of the shoot apex. Plants in 55-mL containers flowered later than those in 166-mL containers (Fig. 3), but shoot dry mass and leaf area were similar in both treatments at the end of the experiment. The shoots of the plants in the 510-mL containers were much larger than those in the smaller containers, partly because of considerable lateral branching (data not shown). This prevented the growth rate from decreasing dramatically after flower initiation. *Salvia* apparently needs more than 166 mL of root zone volume to produce significant lateral shoot growth. Dubik et al. (1989) reported that most of the reduction in growth of euonymus (*Euonymus kiautschovica* Loes.) resulting from root restriction was caused by a decrease in growth of lateral buds. Peterson et al. (1991b) reported that root restriction decreased leaf area of lateral branches more than that of the leaves on the main axis of tomato (*Lycopersicon esculentum* Mill.).

Container volume also affected the shoot : root ratio of the plants. Plants in 166-mL pots tended to have the lowest, while those in the 7.3-mL pots had the highest shoot : root ratio (Table 1). Although there were significant container size effects on shoot : root ratio, there was a close correlation between shoot and root dry mass (Fig. 4). This suggests that the inhibition of root growth by small pot sizes had a major effect on shoot dry mass accumulation.

The slow growth of plants in the 7.3-mL cells was reflected in a low NAR, while the NAR of plants in the other three cells sizes was significantly higher (Table 1). Leaf area ratio decreased during plant development (data not shown), but there was no significant interaction between DAP and container volume. Averaged over the entire growing period, LAR was highest in the 7.3-mL pots, followed by the 510-mL pots, and lowest in the 55- and 166-mL pots (Table 1). The growth differences among the plants in the 55-, 166-, and 510-mL containers can be explained by the higher LAR in 510-mL pots. This, combined with a similar NAR, resulted in faster growth of the plants in the 510-mL containers. Plants in the 55- and 166-mL containers had a similar NAR and LAR, resulting in only small differences in plant size at the end of the experiment.

RGR of the plants in 7.3-mL cells initially was lower than that in the other three treatments and decreased during development. This decrease in RGR was most rapid in the 166-mL pots and slowest in the 7.3-mL ones (Fig. 5). Plants in 510-mL pots had the highest RGR over the course of the experiment, although plants in 7.3-mL pots had the highest RGR at the end of the experiment. A drop in RGR typically occurs during the development of a plant and depends on changes in LAR and

NAR (Květ et al., 1971). Net assimilation rate normally decreases during plant development (Thorne, 1960), partly because of an increase in intraplant shading as the plants grow (Květ et al., 1971). Both LAR and NAR of salvia decreased during the course of this experiment (data not shown), resulting in a decrease in RGR.

The lower LAR in the 55- and 166-mL containers was at least partly caused by inhibition of leaf expansion. The size of individual leaves increased with increasing container size (data not shown). Peterson et al. (1991a) reported that root restriction of tomato reduced concentrations of free indole-3-acetic acid (IAA) in the leaves and concluded that the low IAA levels were responsible for the reduction in leaf area. Carmi and Heuer (1981) showed that a combination of gibberellic acid and benzyladenine could reverse the effects of root restriction on the growth of the stem and primary leaves of bean (*Phaseolus vulgaris* L.). The effects of root restriction on shoot growth may be mediated by several hormones, but these interactions are not clearly understood. Leaf expansion can also be affected by the water status of leaves. Cell expansion is one of the plant processes most sensitive to a water deficit (Hsiao, 1973) and a decrease in turgor pressure can greatly limit cell and leaf enlargement. However, root restriction reduces leaf area even when water is readily available (Bar-Tal et al., 1995; Dubik et al., 1990). In this study, water stress may have contributed to the differences in leaf area and plant growth, especially in the 7.3-mL cells. Water stress normally causes a reduction in NAR (Květ et al., 1971) and this may explain the lower NAR of the plants in the 7.3-mL cells. Since the NARs of the plants in the other three treatments were similar (Table 1), water deficits were probably not an important factor in restricting growth of plants in the larger pot sizes. The similar NARs of the plants in the three largest containers corroborates the findings of Thomas and Strain (1991), who found that the photosynthetic rate of cotton (*Gossypium hirsutum* L.) leaves was not affected by root restriction when the plants were grown at a concentration of 350 ppm CO₂. In contrast, NeSmith et al. (1992) and Ismail and Noor (1996) reported that root restriction decreased the photosynthetic rate of pepper (*Capsicum annuum* L.) and starfruit (*Averrhoa carambola* L.) leaves.

Another possible cause of growth differences in root restriction studies is nutrient availability. If plants are fertilized with the same nutrient solution, then larger pots will supply larger amounts of fertilizer. This can be partly compensated by increasing fertilizer concentrations for plants in smaller pots, but this in turn will affect the osmotic potential of the growing mix. However, Bar-Tal et al. (1995) showed that reduction in dry matter production of root-restricted tomato was not caused by nitrogen deficiency. Because most growers fertilize their bedding plant crop with little consideration for container volume, the same fertilizer concentration was used in all treatments in this study, yet no symptoms of nutrient deficiency were observed.

Aeration of the growing medium may also be affected by cell size (Dubik et al., 1989). The high root density in small containers may have reduced the amount of air space in the growing medium, restricting diffusion of O₂ into and CO₂ out of the containers. This may have led to anaerobic conditions in the root

zone and reduced root activity. On the other hand, the distance over which gases diffuse is much shorter in small cells than in larger pots. This would have favored better aeration in smaller pots. Thus the exact effect that root restriction had on O₂ and CO₂ in the growing medium remains unknown. The pH of the

Fig. 2. Effect of container volume on leaf area of salvia (container volume: ∇ , 7.3 mL, $\blacktriangledown$ 55 mL, $\bigcirc$ 166 mL, and $\bullet$ 510 mL). Mean separation within days by Fisher's protected LSD_{0.05}.

Fig. 3. Effect of container volume on flowering of salvia (container volume: ∇ 7.3 mL, $\blacktriangledown$ 55 mL, $\bigcirc$ 166 mL, and $\bullet$ 510 mL). Plants were considered to be flowering if they had a flower bud >1 cm in diameter. Data represent the mean $\pm$ standard error.

Fig. 4. Effect of container volume on root and shoot dry mass of salvia (container volume: ∇ 7.3 mL, $\blacktriangledown$ 55 mL, $\circ$ 166 mL, and $\bullet$ 510 mL). Regression line: $Y = -0.013 + 2.87 \times X$, $r^2 = 0.93$, $P < 0.0001$.

Fig. 5. Effect of container volume on relative growth rate (RGR) of salvia (container volume: ---- 7.3 mL, ... 55 mL, - · - 166 mL, — 510 mL). Relative growth rates were estimated as the first derivative of second order polynomial functions, fitted to the dry mass data after natural log transformation.

growing mixes may also have differed among cell sizes, but was not measured during this experiment.

Time to flowering decreased with increasing container volume (Fig. 3). This was especially noticeable for the plants in 7.3-mL pots. None of these plants flowered until 62 DAP, while 80% or more of the plants in the other three treatments was flowering at this stage. Almost all (96%) the plants in the three largest pot sizes flowered at 67 DAP, while only 61% of the plants in 7.3-mL cells flowered. Previ-

ous reports on root restriction and flowering indicate that the response may be species-dependent. Flowering of bell pepper, cotton, and starfruit was hastened by root restriction (Carmi, 1986; Ismail and Noor, 1996; NeSmith et al., 1992), while flowering of tomato was delayed (Ruff et al., 1987) and timing and duration of flowering of summer squash (*Cucurbita pepo* L.) was not affected (NeSmith, 1993).

In summary, increasing container volume results in larger salvia plants with more lateral

growth, hence improving plant quality. Larger containers also hasten flowering of salvia, which can shorten the production cycle by several days. This suggests that transplanting plugs earlier also may help reduce the production period of salvia. Commercial growers must weigh the advantages of larger pots against the disadvantage of having plants per unit area to decide what container volume is optimal for their specific situation. If larger pots are selected, care should be taken that the pot size allows for lateral growth of the plants. Otherwise, the advantages of increasing pot size are small, while reducing the number of plants per unit area by 55% (i.e., 55- vs. 166-mL pots).

Literature Cited

- Bar-Tal, A. and E. Pressman. 1996. Root restriction and potassium and calcium solution concentrations affect dry-matter production, cation uptake, and blossom-end rot in greenhouse tomato. *J. Amer. Soc. Hort. Sci.* 121:649–655.
- Bar-Tal, A., A. Feigin, S. Sheinfeld, R. Rosenberg, B. Sternbaum, I. Rylski, and E. Pressman. 1995. Root restriction and N-NO₃ solution concentration effects on nutrient uptake, transpiration and dry matter production of tomato. *Scientia Hort.* 63:195–208.
- Carmi, A. 1986. Effects of root zone volume and plant density on the vegetative and reproductive development of cotton. *Field Crops Res.* 13:25–32.
- Carmi, A. and B. Heuer. 1981. The role of roots in control of bean shoot growth. *Ann. Bot.* 48:519–527.
- Dubik, S.P., D.T. Krizek, and D.P. Stimart. 1989. Influence of root zone restriction on morphogenetic responses of spreading euonymus (*E. kiautschovica* Loes. 'Sieboldiana'). *J. Plant Nutr.* 12:1021–1044.
- Dubik, S.P., D.T. Krizek, and D.P. Stimart. 1990. Influence of root zone restriction on mineral element concentration, water potential, chlorophyll concentration, and partitioning of assimilate in spreading euonymus (*E. kiautschovica* Loes. 'Sieboldiana'). *J. Plant Nutr.* 13:677–699.
- Hanson, P.J., R.K. Dixon, and R.E. Dickson. 1987. Effect of container size and shape on the growth of northern red oak seedlings. *HortScience* 22:1293–1295.
- Hsiao, T.C. 1973. Plant responses to water stress. *Annu. Rev. Plant Physiol.* 24:519–570.
- Hunt, R. 1982. Plant growth curves. The functional approach to plant growth analysis. University Park Press, Baltimore.
- Ismail, M.R. and K.M. Noor. 1996. Growth, water relations and physiological processes of starfruit (*Averrhoa carambola* L.) plants under root growth restriction. *Scientia Hort.* 66:51–58.
- Květ, J., J.P. Ondok, J. Nečas, and P.G. Jarvis. 1971. Methods of growth analysis, p. 343–391. In: Sesták, Z., J. Catský, and P.G. Jarvis (eds.). Plant photosynthetic production. Manual of methods. Dr. W. Junk N.V., Publishers, The Hague.
- Latimer, J.G. 1991. Container size and shape influence growth and landscape performance of marigold seedlings. *HortScience* 26:124–126.
- Marsh, D.B. and K.B. Paul. 1988. Influence of container type and cell size on cabbage transplant development and field performance. *HortScience* 23:310–311.
- Maynard, E.T., C.S. Vavrina, and W.D. Scott. 1996. Containerized muskmelon transplants: Cell volume effects on pretransplant development and subsequent yield. *HortScience* 31:58–61.
- NeSmith, D.S. 1993. Influence of root restriction on

- two cultivars of summer squash (*Cucurbita pepo* L.). J. Plant Nutr. 16:421-431.
- NeSmith, D.S., D.C. Bridges, and J.C. Barbour. 1992. Bell pepper responses to root restriction. J. Plant Nutr. 15:2763-2776.
- Peterson, T.A., J.D. Cohen, J.G. Buta, and D.T. Krizek. 1991a. Influence of root restriction on tomato: Changes in leaf cell expansion, abscisic acid and indole-3-acetic acid. Plant Physiol. 96(suppl.):78.
- Peterson, T.A., M.D. Reinsel, and D.T. Krizek. 1991b. Tomato (*Lycopersicon esculentum* Mill., cv. 'Better Bush') plant response to root restriction. I. Alteration of plant morphology. J. Expt. Bot. 42:1233-1240.
- Peterson, T.A., M.D. Reinsel, and D.T. Krizek. 1991c. Tomato (*Lycopersicon esculentum* Mill., cv. 'Better Bush') plant response to root restriction. II. Root respiration and ethylene generation. J. Expt. Bot. 42:1233-1240.
- Ruff, M.S., D.T. Krizek, R.M. Mirecki, and D.W. Inouye. 1987. Restricted root zone volume: Influence on growth and development of tomato. J. Amer. Soc. Hort. Sci. 112:763-769.
- Thomas, R.B. and B.R. Strain. 1991. Root restriction as a factor in photosynthetic acclimation of cotton seedlings grown in elevated carbon dioxide. Plant Physiol. 96:627-634.
- Thorne, G.N. 1960. Variations with age in net assimilation rate and other growth attributes of sugarbeet, potato, and barley in a controlled environment. Ann. Bot. 24:356-371.
- Tilt, K.M., T.E. Bilderback, and W.C. Fonteno. 1987. Particle size and container size effects on growth of three ornamental species. J. Amer. Soc. Hort. Sci. 112:981-984.
- Waters, L.J., R.L. Burrows, M.A. Bennett, and J. Schoenecker. 1990. Seed moisture and transplant mangement techniques influence sweet corn stand establishment, growth, development, and yield. J. Amer. Soc. Hort. Sci. 115:888-892.
- Weston, L.A. 1988. Effect of flat cell size, transplant age, and production site on growth and yield of pepper transplants. HortScience 23:709-711.
- Weston, L.A. and B.H. Zandstra. 1986. Effect of root container size and location of production on growth and yield of tomato transplants. J. Amer. Soc. Hort. Sci. 111:498-501.