ABSTRACT

DONNELL, ALIYA AFI. Effect of plug flat on plant growth and prevention of post-transplant stunting. (Under the direction of John M. Dole).

Plugs should be transplanted at the pullable plug stage (PPS), which is when the root ball holds together after removal from the plug flat. If seedlings are held in plug flats for too long after PPS, they may not return to a normal growth rate after transplanting. This may be due to several factors including nutrient deficiency, hormone deficiency, low oxygen availability, water stress, altered light quality and quantity, the mechanism of the root hitting the edge of the container and the inability of rootballs to expand once transplanted. The objectives of this study were to: 1) determine which floriculture crops are sensitive to stunting caused by plug flats; 2) determine possible causes of post-transplant stunting; and 3) examine methods of overcoming plug stunting and the inability of plants to return to a normal growth rate after transplanting.

Effect of plug flat on plant growth. In the fall of 2003 and the spring of 2004, *Antirrhinum* L. 'Floral Showers Coral Bicolor', *Begonia* L. 'Harmony Pink', *Brassica* L. 'Red Peacock', *Callistephus* L. (Nees) 'Matsumoto Rose', *Celosia* L. 'Century Red', *Consolida* (L.) P.W. Ball & Hey. 'Pink Fantasy', *Dianthus* L. 'Telstar Picotee', *Eustoma* (Raf.) Shinn. 'Balboa Purple, *Gazania* L. 'Daybreak Mix', *Impatiens* Hook. F. 'Dazzler Red', *Lycopersicon* Mill. 'Heartland', *Matthiola* (L.) R. 'Christmas Ruby' and 'Harmony Cherry Blossom; *Tagetes* L. 'Little Devil Fire', and *Viola* L. 'Starlet Rose with Blotch' were grown in 200 or 288 plug flats until PPS. Species that exhibited stunting included *Brassica, Callistephus, Celosia, Consolida, Dianthus,* and *Tagetes*. The remaining

species were not affected by the amount of time held in the plug flat after PPS. These species allow the industry more flexibility in terms of transplanting time. Further research needs to be conducted examining other species and their reactions to being held in plug flats after the optimal transplanting time.

Prevention of post-transplant stunting. Beginning in the fall of 2004, seed of *Catharanthus* L. 'Pacifica Lilac' and/or *Celosia* L. 'Century Red' or 'Century Fire' was sown into 288 size (7.3 ml) plug flats and subjected to such treatments as pre-transplant nitrogen application, pre-transplant gibberellic acid application, root obstruction, pre-transplant root ball disturbance, and longer drainage columns. In addition, four of the experiments included a control with seeds sown directly into 17 cm (1.66 L) pots. Plants directly sown into 17 cm (1.66 L) pots were significantly larger than both control and treated plugs. Only two treatments made consistent differences in post-transplant growth. Growing plugs on a longer drainage column led to a significantly larger final diameter in *Celosia* 'Century Fire' plugs transplanted on time. This leads us to believe that low oxygen availability could be one cause of plug stunting and the inability to regain a normal growth rate after transplanting. Also, root obstructed plugs were 5.1 cm smaller than control plants at transplanting, but there was no difference in the height of root obstructed plants and control plants after eight weeks. This suggests that root obstruction may be a contributing, but temporary factor to plug stunting and may allow for plugs to be held longer in the plug flat without sacrificing final plant quality.

In summary, our study confirms that post-transplant stunting due to excessive holding in plug flats is a problem in some species. Two of the methods evaluated for overcoming this problem proved to be successful. This information will allow plug users to better manage the growth of plugs after transplanting.

EFFECT OF PLUG FLAT ON PLANT GROWTH AND PREVENTION OF POST-TRANSPLANT STUNTING

By

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A thesis submitted to the Graduate Faculty of
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requirements for the Degree of
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BIOGRAPHY

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In her spare time, she enjoys listening to music, gardening, movies, watching reality tv, playing with her dog and spending time with friends and family.

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CHAPTER I

INTRODUCTION

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This research would not be possible without the help of Diane Mays. Appreciation is also expressed to Ingram McCall, Dr. Judith Thomas, Dr. Bill Fonteno, William Reese and Reneé Donnell.

Additional index words. Plug flat, bedding plants, cut flowers, stunting, transplants, seedlings, pullable plug stage (PPS).

Within the past 15 to 20 years, plug production has become an integral part of the floriculture industry. More than 90% of all bedding crops are now grown using plugs, and recent statistics show that approximately 25 billion plugs were produced in the US and Canada alone (Styer and Koranski, 1997). Plug production is important outside of North America as well. In Europe, for example, nearly 100% of cut flowers started from seed are produced from plugs (Styer and Koranski, 1997). In Australia, a high percentage of bedding plants are produced from plugs. Plug technology has spread to most parts of the world including Korea, Japan, Israel, South Africa, Colombia, Central America, and Mexico.

Plugs can be defined as containerized transplants. In plug production, seeds are sown or cuttings are propagated into the cells of plug flats and kept in the cells until transplanted. Before plugs were used, seeds were sown directly into seedbed flats and were transplanted from them. Because the roots were not self-contained, many were broken off during transplanting, leading to root rot and uneven growth from transplant shock. With plugs roots are self-contained. Once transplanted, seedlings grown from plugs are healthier and less susceptible to root rot and other diseases, and resume growth more rapidly due to reduced transplant shock (Styer and Koranski, 1997). Styer and Koranski (1997) describe four stages of plug production. In Stage One, the radicle emerges from the seed and in Stage Two, it penetrates the growing medium. In Stage Three, true leaves begin to grow and develop and in Stage Four, the seedlings are finally ready for shipping and transplanting. Plugs should be transplanted at the pullable plug stage (PPS), which occurs at the end of Stage Four when the plug's rootball is sufficiently developed to hold together after removal from the plug flat. The amount of time in weeks necessary to reach PPS varies by species, but for *Celosia* and *Catharanthus* it ranges from 12-14 weeks after sowing.

There are many advantages to plug production, including less time and labor required to transplant seedlings, more uniform post-transplant growth and increased production per square foot (Styer and Koranski, 1997). Also, plugs are less susceptible to root rot and transplant shock during and after transplanting. Though the advantages to producing transplants in plugs are numerous, there are a few disadvantages. Specially trained people are needed to sow plugs, it takes longer to produce a plug than a seedling flat, and the cost of plugs is greater per seedling than seedling flats. In addition, studies have shown that with some species, plants left in plug flats for too long after PPS exhibit premature flowering, apical dominance, and stunting (Latimer, 1991; van Iersel, 1997). However, some species are not affected by remaining in the plug flats for long durations. These species eventually "catch up" after transplanting and exhibit normal growth patterns.

If not transplanted promptly, plugs can be held in the greenhouse for up to two weeks by lowering the temperature to 10 to 15^{o} C, increasing the light level greater than 500 $\mu mol \cdot m^{-2} \cdot s^{-1}$, restricting water applications, switching to nitrate-based fertilizers, reducing fertilization rate, and applying plant growth regulators (Styer and Koranski, 1997). These actions, however, may increase the likelihood of early flowering, especially with sensitive species such as *Callistephus* L. (Nees), *Celosia* L., *Consolida* (L.) P.W. Ball & Hey., *Eustoma* (Raf.) Shinn., *Tagetes* L., and *Zinnia* L.

While the best option for preventing stunting and early flowering of plugs is to promptly transplant them, lack of production space or labor can greatly delay planting schedules at times. Long-term storage (up to 11 weeks) may be possible by placing the seedlings in a cooler (Heins et al., 1995.) However, many species are not tolerant of temperatures low enough to slow growth significantly. Cooling the plugs may delay problems, but the potential for stunting and early flowering still exists. With some bedding plants, the stunting may be beneficial at times to produce a compact, rapidly flowering flat of plants. However, for all cut flower species and many potted flowering and bedding plant species, stunting and early flowering reduce final plant quality. In addition, cut flower species such as *Consolida ambigua* and *Ammi majus* L. rarely produce high quality stems from plugs but regularly produce long, high quality stems from direct-seeding in the field or greenhouse bed (Styer and Koranski, 1997). Apparently, such species are stunted when grown in plugs no matter how short the cultivation period in the plug flat. Previous research has focused on the effect of restricted root volumes on final plant performance. However, little research has been conducted on the effect of amount of time in the plug flat on final transplant performance.

A number of factors are thought to affect the performance of plugs in the flat or after they are transplanted, including limitations in nutrient uptake, hormone deficiency, water stress, low oxygen availability, the root hitting the container, the inability of the rootball to expand after transplanting, and light quantity and/or quality.

Limitations in nutrient uptake may cause stunting of plants grown in plug flats and the inability to return to a normal growth rate after transplanting. According to van Iersel et al. (1998; 1999), the amount of nutrient received by plugs is often not sufficient for pre- or post-transplant growth. The recommended fertilizer nitrogen concentration for plugs, 3.5 to 11 mM once or twice weekly (Styer and Koranski, 1997), was too low for successful plug growth rates after transplanting *Catharanthus, Impatiens* Hook. F., *Petunia* (Hook.) Schinz & Thellung, and *Salvia* L. plugs. van Iersel et al. (1998) found that the greatest post-transplant growth occurred when 16 to 32 mM nitrogen was used on *Petunia* and *Impatiens* plugs. In *Catharanthus* and *Salvia* L. plugs pre- and post-transplant growth was linearly correlated with increasing N concentration from 8 mM to 32 mM (van Iersel et al., 1999). In addition, phosphorus and potassium fertilizer levels were not as crucial as nitrogen to the successful growth of plugs after transplanting (van Iersel et al., 1998; 1999).

Hormone deficiency has also been examined in many studies as a possible cause of plug stunting. The restricted root zone volume of the plug flat may cause plants to produce lower amounts of hormones, namely gibberellins (GA) and cytokinins, necessary for normal growth and development (Dubik et al., 1989; Carmi and Heuer, 1980; Ismail and Noor, 1996; Lui and Latimer, 1995). A decrease in the transport of GA and cytokinins from the roots to the shoot leads to a reduction in shoot growth. Gibberellins are synthesized in the roots and are responsible for shoot elongation. Cytokinins are also synthesized in the roots and promote cell division. An increase in the presence of abscisic acid (ABA), a growth inhibitor, has also been hypothesized (Liu and Latimer, 1995). Abscisic acid helps plants respond to physiological stress by inhibiting growth. For example, Liu and Latimer (1995) determined that root restriction increased levels of absisic acid produced by the roots in *Citrullus lanatus* (Thunb.) Matsumura & Nakai seedlings. The ABA was transported to the shoots via xylem sap, where it inhibited shoot growth. Higher absisic acid levels were measured in the roots of seedlings grown in smaller plug sizes than larger ones. Carmi and Heuer (1980) were able to overcome the stunting of *Glycine max* L. seedlings grown under root zone restriction with the application of GA and benzyladenine, a cytokinin. Therefore, they concluded that a reduction in transport of GA and cytokinins to the shoot from the root is responsible for the stunting of plants grown under rooting volume restriction.

Another possibility for the stunting of plugs is low oxygen availability. If oxygen is not available to the roots, root respiration is significantly reduced, which affects other metabolic processes within the plant. Responses to low oxygen availability are similar to those caused by soil compaction, waterlogging, and limited aeration including reduced leaf growth, epinasty, root death, reduced branching, and lower transpiration levels (Peterson et al., 1991). The high-density root environments of small containers increase the competition for oxygen. For example, in small volume containers, more of the soil pore space is occupied by roots than in larger containers. This increase in root density leads to an increase in competition for resources and the oxygen supply to the inner roots is severely limited (Peterson et al., 1991). Peterson et al. (1991) reported that new roots tend to develop close to the source of nutrients and oxygen. In doing so, they form a barrier to the oxygen supply for other roots in the containers, therefore restricting the amount of oxygen available to the rest of the roots. Dubik et al. (1989) also suggest that poor aeration could be a cause for the alteration in shoot growth in plants grown in restricted root volumes. They hypothesize that poor aeration affects the oxygen available to all roots because of reduced surface area for air exchange, limited physical space within the container available for gas exchange, and increased effects of compaction due to settling of the medium, which would be more likely to occur in small containers than in large ones.

Water stress may also stunt plants grown with restricted rooting volumes. Many studies have shown that even when water is not limited, plants grown in small containers demonstrate drought stress symptoms (Hameed et al., 1987; Kharkina et al., 1999). These symptoms include smaller leaf area, thicker leaves, wilting in the afternoon, and decreased transpiration rate (Hameed et al., 1987). Kharkina et al. (1999) suggested that the reason for drought stress symptoms in root restricted plants is the inability of roots to absorb and transport water due to the physical limitation of root volume in relation to the size of the shoots. Inability to absorb water may also be due to the decrease in root hair initiation and formation of lateral roots (Krizek et al., 1985). Hanson et al. (1987) found that plants grown under conditions of root restriction demonstrated reduced root pressure, which led them to assume that the plants were under some water stress, though the plants had been adequately watered. In contrast, many studies have shown that water stress is not apparent if plants are irrigated frequently (Krizek et al., 1985; Carmi and Heuer, 1980; Ismail and Noor, 1996; Peterson et al., 1991). Krizek et al. (1985) indicated that leaf water potentials, stomatal conductance, assimilate distribution, carbohydrate concentration, nitrogen concentration, and other factors differ between plants subjected to soil moisture stress and restricted root zone volume. Other studies show that while water stress is a factor, it is probably not the most important factor in the stunting of plants grown in small containers (van Iersel, 1997). Water stress can also be caused by the presence of concentrated amounts of soluble salts in the media. When this occurs, the plant is unable to absorb sufficient water, because the water potential is greater in the media water solution than in the root and more energy is needed for water uptake.

Other possible causes include the root hitting the container and the inability of a root-bound rootball to expand after transplanting. Rootballs that have been in small containers for long amounts of time may become root-bound and have trouble expanding after transplanting. Gouin (1984) states that root-bound plants are slow to establish and more susceptible to drought stress because their roots continue to grow in a circular manner after transplanting and expand into the soil very slowly. The longer the plant is held in a container, the worse these symptoms become. In the nursery industry, it is recommended that root-bound plants be root pruned to stimulate root branching and help them establish more quickly in the landscape (Gouin, 1984). Root pruning can be either mechanical or chemical. Mechanical root pruning involves slashing the root ball at various points, while chemical root pruning uses a chemical (usually a copper compound) to help roots avoid the container surface. However, though mechanical pruning has been long recommended, Arnold (1996) found that mechanically pruned *Quercus shumardii*

Buckl. plants experienced more water stress just after transplanting than plants that were chemically pruned or not pruned at all. Struve (1993) found that there was no difference in height after three years between *Acer rubrum* L., *Liquidambar styraciflua* L., *Quercus rubra* L., and *Quercus coccinea,* Muenchh. plants that had been root pruned and those that had not.

Lastly, both light quality and light quantity are possible causes of stunting in plug flats. The red: far-red ratio could be a factor in high density planting situations, such as greenhouses and other agricultural systems. Plant tissue absorbs almost all red light and reflects or transmits most far-red light. Therefore, plants in high density situations, such as plug flats, receive more far-red light than red light. Red light is used primarily for photosynthesis. Far-red light, on the other hand, causes stem elongation, reduced branching, and premature flowering (Ballare et al., 1995). Plants can sense the proximity of other plants due to far-red light reflected off neighboring plants even before the canopy closes. *Hordeum vulgare* L. plants grown in close proximity to other *Hordeum vulgare* plants exhibited an earlier transition to reproductive growth and fewer main shoot leaves than plants grown in less dense situations (Davis and Simmons, 1994).

Light quantity considers the amount of light received by a plant. In plug flats, the seedlings often shade each other, reducing the amount of light available to each seedling. NeSmith (1993) determined that photosynthetically active radiation (PAR) was more of a limiting factor than root restriction in the dry weight accumulation of *Cucurbita moschata* (Duchesne ex Lam.) Duchesne ex Poir., and that plants seemed to be more sensitive to low levels of PAR than to root restriction.

Objectives

The research has 3 objectives:

1. To determine which floriculture crops are sensitive to stunting caused by plug flat holding;

2. To determine possible causes of post-transplant stunting due to plugs being held too long after PPS;

3. To examine methods of overcoming plug stunting and the inability of plants to return to a normal growth rate after transplanting.

Literature Cited

Arnold, M. A. 1996. Mechanical correction and chemical avoidance of circling roots differentially affect post-transplant root regeneration and field establishment of container-grown shumard oak. J. Ameri. Soc. Hort. Sci. 121:258-263.

Ballare', C.L., A.L. Scopel, and R. A. Sanchez. 1995. Plant morphogenesis in canopies, crop growth, and yield. HortScience 30:1172-1181.

Carmi, A. and B. Heuer. 1981. The role of roots in control of bean shoot growth. Ann. Bot. 48:519-527.

Davis, M.H. and S.R. Simmons. 1994. Far-red light reflected from neighboring vegetation promotes shoot elongation and accelerates flowering in spring barley plants. Plant, Cell and Environ. 17:829-836.

Dubik, S.P., D.T. Krizek, and D.P. Smart. 1989. Influence of root zone restriction on morphogenetic responses of spreading euonymus. J. Plant Nutr. 12:1021-1044.

Gouin, F.R. 1984. Updating Landscape Specifications. J. Environ. Hort. 2:98-101

Hameed, M.A., J.B. Reid, and R.N. Rowe. 1987. Root confinement and its effects on the water relations, growth and assimilate partitioning of tomato. Annals Bot. 59:685-692.

Hanson, P.J., R.K. Dixon, R.E. Dickson. 1987. Effect of container size and shape on the growth of northern red oak seedings. HortScience 22:1293-1295.

Heins, R.D., M.P. Kaczperski, T.F. Wallace Jr., N.E. Lange, W.H. Carlson, and J.A. Flore. 1995. Low-temperature storage of bedding plant plugs. Acta Hort. 396:285-296.

Ismail, R.M. and K.M. Noor. 1996. Growth, water relations and physiological processes of starfruit plants under root growth restriction. Scientia Hort. 66:51-58.

Kharkina, T.G., C.O. Ottosen, and E. Rosenqvist. 1999. Effects of root restriction on the growth and physiology of cucumber plants. Physiol. Plant. 105:434-441.

Krizek, D.T., A. Carmi, R.M. Mirecki, F.W. Snyder, and J.A. Bunce. 1985. Comparative effects of soil moisture stress and restricted root zone volume on morphogenetic and physiological responses of soybean. J. Expt. Bot. 36:25-38.

Latimer, J.G. 1991. Container size and shape influence growth and landscape performance of marigold seedlings. HortScience 26: 124-126.

Liu, A. and J.G. Latimer. 1995. Water relations and abscisic acid levels of watermelon as affected by rooting volume restriction. J. Expt. Bot. 46:1011-1015.

NeSmith, D.S. 1993. Summer squash response to root restriction under different light regimes. J. Plant Nutr. 16:765-780.

Peterson, T.A., M.D. Reinsel, and D.T. Krizek. 1991. Tomato plant response to root restriction: Root respiration and ethylene generation. J. Expt. Bot. 42:1241-1249.

Struve, D.K. 1993. Effect of copper-treated containers on transplant survival and regrowth of four tree species. J. Environ. Hort. 11:196-199.

Styer, R.C. and D.S. Koranski. 1997. Plug and transplant production: a grower's guide. Ball Publishing, Batavia Ill.

van Iersel, M. 1997. Root restriction effects on growth and development of salvia. HortScience 32:1186-1190.

van Iersel, M., P.A. Thomas, R.B. Beverly, J.G. Latimer and H.A. Mills. 1998. Nutrition affects pre- and post-transplant growth of impatiens and petunia plugs. HortScience 33: 1014-1018.

van Iersel, R.B. Beverly, P.A. Thomas, J.G. Latimer, and H.A. Mills. 1999. Nitrogen, phosphorus, and potassium effects on pre- and post-transplant growth of salvia and vinca seedlings. J. Plant Nutr. 22: 1403-1413

CHAPTER II

EFFECT OF PLUG FLAT HOLDING ON PLANT GROWTH

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This research would not be possible without the help of Diane Mays. Appreciation is also expressed to Ingram McCall, Dr. Judith Thomas and Dr. Bill Fonteno.

Additional index words. Plug flat, bedding plants, cut flowers, stunting, transplants, seedlings, pullable plug stage (PPS).

Abstract. Plugs should be transplanted at the pullable plug stage (PPS), which is when the root ball holds together after removal from the plug flat. If seedlings are held in plug flats for too long after PPS, they may not return to a normal growth rate after transplanting. In the fall of 2003 and the spring of 2004, *Antirrhinum* L. 'Floral Showers Coral Bicolor', *Begonia* L. 'Harmony Pink', *Brassica* L. 'Red Peacock', *Callistephus* L. (Nees) 'Matsumoto Rose'*,* *Celosia* L. 'Century Red', *Consolida* (L.) P.W. Ball & Hey. 'Pink Fantasy', *Dianthus* L. 'Telstar Picotee', *Eustoma* (Raf.) Shinn. 'Balboa Purple, *Gazania* L. 'Daybreak Mix', *Impatiens* Hook. F. 'Dazzler Red', *Lycopersicon* Mill. 'Heartland', *Matthiola* (L.) R. 'Christmas Ruby' and 'Harmony Cherry Blossom; *Tagetes* L. 'Little Devil Fire', and *Viola* L. 'Starlet Rose with Blotch' were grown in 200 or 288 plug flats to determine how long plugs could be held in the flats and still regain a normal

growth rate and desirable growth form after transplanting. A plug was considered to be stunted if it died after transplanting or did not resume a normal growth rate. Species that exhibited stunting included *Callistephus, Celosia, Consolida, Dianthus,* and *Tagetes*. For example, in the spring study, *Consolida* seedlings held in the plug flat for six weeks after PPS were six times smaller than those transplanted at the optimal time. The remaining species were not affected by the amount of time held in the plug flat after PPS. These species allow the industry more flexibility in terms of transplanting time. Further research needs to be conducted examining other species and their reactions to being held in plug flats after the optimal transplanting time.

Introduction

Plants grown in restricted root volumes, such as plug flats, often exhibit premature flowering, apical dominance, and stunting after transplanting (Latimer, 1991; van Ierasel, 1997). Plugs should be transplanted at the pullable plug stage (PPS), which occurs at the end of Stage 4 of plug production (Styer and Koranski, 1997), when the plug's rootball is sufficiently developed to hold together after removal from the plug flat. Many growers have reported that for most species, final transplant performance of plugs is not affected if plugs are transplanted on time. However, with some species, plants left in plug flats for too long after PPS exhibit premature flowering, apical dominance and stunting after transplanting (D. Etheridge, personal communication). Other species are not affected by remaining in the plug flats for long durations. These species eventually "catch up" after transplanting and exhibit normal growth patterns. With some bedding plants, the stunting may be beneficial to produce a compact, rapidly flowering flat of plants. However, for all cut flower species and many potted flowering and bedding plant species, stunting and early flowering reduce final plant quality. In addition, cut flower species such as *Consolida ambigua* (L.) P.W. Ball & Hey. and *Ammi majus* L. rarely produce high quality stems from plugs but regularly produce long, high quality stems from direct-seeding in the field or greenhouse bed (Styer and Koranski, 1997). Apparently, such species are stunted when grown in plugs no matter how short the cultivation period in the plug flat. Previous research has focused on the effect of restricted root volumes on final plant performance. However, little research has been done on the effect of amount of time in the plug flat on final transplant performance.

Stunting and early flowering can be due to delayed transplanting with some species or simply due to cultivation in plug flats for other species. The objective is to determine which floriculture crops are sensitive to the negative effects caused by plug flat holding.

Materials and Methods

Fall species. Seed of *Antirrhinum* L. 'Floral Showers Coral Bicolor', *Brassica* L. 'Red Peacock', *Dianthus* L. 'Telstar Picotee', *Gazania* L. 'Daybreak Mix', *Matthiola* (L.) R. 'Harmony Cherry Blossom' and 'Christmas Ruby', and *Viola* L. 'Starlet Rose with Blotch' were sown in 288 (7.3 ml/cell) size plug flats in a peat-based commercial substrate (Fafard 4P, Conrad Fafard, Inc. Agawam, Mass.). Seed of *Consolida* 'Pink Fantasy' were sown in a 200 size plug flat (11.2 ml/cell). Transplanting commenced when root balls reached PPS. For each species, ten randomly selected plugs from one plug flat were transplanted to 15 cm (1.29 L) pots every week for 5 weeks. Overall plant height (from top of pot to the highest point of the plant) was recorded each week. The experiment was conducted in North Carolina State University Horticulture Greenhouses with target temperatures of 75°F during the day and 65°F at night. Data were analyzed by the general linear model procedure (SAS Institute, Cary, NC). Least significant difference (LSD) was used for mean separation of initial and final heights between treatments. Differences in growth (stem elongation) rates were calculated using contrast statements comparing slopes between treatments.

Spring species. Seed of *Begonia* L. 'Harmony Pink', *Celosia* L. 'Century Red', *Callistephus* L. 'Matsumoto Rose', *Consolida* (L.) P.W. Ball & Hey. 'Pink Fantasy', *Eustoma* (Raf.) Shinn. 'Balboa Purple', *Impatiens* Hook. F. 'Dazzler Red', *Lycopersicon* Mill. 'Heartland', and *Tagetes* L. 'Little Devil Fire' were sown in 288 (7.3 ml) size plug flats in a peat-based commercial substrate (Fafard 4P, Conrad Farfard, Inc., Agawam, Mass.). Transplanting commenced at PPS. Ten randomly selected plugs were transplanted to 17 cm (1.66 L) pots every two weeks for 8 weeks and placed in a completely randomized design with 10 single plant replications (pots) per treatment. Overall plant height (from top of the pot to the highest point on the plant) was recorded every two weeks. In addition, inflorescence length (from the base to the tip of the inflorescence) was recorded for *Consolida* and *Callistephus* every two weeks. Anthesis date was recorded for all species. Plant diameter (average of two measurements, one perpendicular to the other) was taken every two weeks for eight weeks on *Begonia, Celosia, Eustoma, Impatiens, Lycopersicon,* and *Tagetes.* The experiment took place at the Horticulture Field Laboratory Greenhouses at North Carolina State University. Average temperatures ranged from 64° to 79°F throughout the study. Data were analyzed using the general linear model procedure (SAS Institute, Cary, NC). Least significant difference was used for mean separation of initial and final height and diameter between treatments. Differences in growth rates were calculated using contrast statements comparing slopes between treatments.

Results

Fall species. The only species negatively affected by being held in the plug flat for too long was *Dianthus* (Tables 2.1 and 2.2, Fig. 2.1). *Dianthus* 'Telstar Picotee' plugs transplanted at PPS had final heights taller (by about 3 cm on average) than plugs transplanted after PPS. Plugs transplanted at PPS also had the fastest stem elongation rate (Tables 2.3 and 2.4).

The remaining species were not negatively affected by being held in the plug flats past PPS. For *Antirrhinum, Consolida* and *Viola*, heights after five weeks were greatest in plants held in the plug flats past PPS (Table 2.2). *Antirrhinum* 'Floral Showers Coral Bicolor' plugs held for four weeks after PPS were the tallest after five weeks. Interestingly enough, these plugs had the slowest growth rate (Table 2.3 and 2.4). However, since they were taller than the other treatments at transplanting (Table 2.1), growth rate did not affect their final performance. *Consolida* 'Pink Fantasy' plugs held for three or four weeks after PPS were taller than those transplanted at zero, one and two weeks after PPS (Table 2.2). Growth rates among the treatments did not differ (Tables 2.3 and 2.4). Plugs transplanted four weeks after PPS were taller than all other treatments at the time of transplanting (Table 2.1), which is not surprising, considering that they grew at the same rate as the smaller plugs (Tables 2.3 and 2.4). *Viola* 'Starlet Rose with Blotch' plugs held in the flat for four weeks after PPS were tallest after five weeks (Table 2.2). Plugs transplanted at PPS had the greatest stem elongation rate (Tables 2.3 and 2.4), but were smallest at the time of transplanting (Table 2.1). Though these plugs grew fastest, they were unable to "catch up" with the rest of the plugs, which elongated while in the flat.

The final heights for *Brassica, Gazania* and both cultivars of *Matthiola* were not significantly different among the treatments (Table 2.2). *Brassica* plugs transplanted at

PPS had the greatest stem elongation rate (Tables 2.3 and 2.4), but this did not lead to a difference in final height. *Gazania* plugs transplanted four weeks after PPS had the greatest height growth rate of all treatments (Table 2.3 and 2.4). These plugs appeared to have a similar growth rate to the other treatments, but elongated more rapidly around the third week after transplanting (Fig. 2.1). However, the increase was not sufficient to cause this treatment to have significantly taller final heights. There was no difference in the growth rate of *Matthiola* 'Christmas Ruby' plugs between treatments (Tables 2.3 and 2.4). *Matthiola* 'Harmony Cherry Blossom' plants did not show a difference between heights after five weeks of measurement (Table 2.2), contrary to the apparent difference shown in Fig. 2.1. This could be due to the wide range of values obtained for this species or to the fact that so many plants died during the course of the experiment. For example, out of 50 plants, only 19 were still alive after five weeks of measurement. Stem elongation rate was greatest in plugs held for zero or one week after PPS (Tables 2.3 and 2.4). These two treatments were also among the smallest at the time of transplanting (Table 2.1), but because of the faster stem elongation rate, they were the same size as the other treatments after five weeks.

Spring species. Species negatively affected by being held in the plug flat for too long included *Callistephus, Celosia, Consolida,* and *Tagetes* (Tables 2.5 and 2.6, Fig. 2.2). For these species, plants transplanted at PPS or within four weeks after PPS were taller than species held in the plug flats for longer periods of time. *Callistephus* 'Matsumoto Rose' plugs transplanted at PPS or two weeks after were taller than those held for four weeks after PPS (Table 2.6). They also had faster stem elongation rates than all other treatments (Tables 2.7 and 2.8). Plants held for six weeks after PPS died six weeks after transplanting. Plants held in the flat for eight weeks after PPS died in the plug flat before transplanting. *Celosia* 'Century Red' plugs transplanted at zero or two weeks after PPS had final heights that averaged 5 cm taller than those transplanted at four, six or eight weeks after PPS. The tallest plants eight weeks after transplanting were those transplanted at PPS (Table 2.6). There was not a clear relationship between amount of time held in the plug flat and final diameter, though plugs transplanted at PPS had the largest diameter at the end of the study (Table 2.6, Fig. 2.2). Both height and diameter growth rates were greatest in plugs transplanted at PPS (Tables 2.7 and 2.8). *Consolida* 'Harmony Pink' showed results different from those obtained in the fall study. Plugs transplanted at PPS had final heights that were about three times taller of those held for longer (Table 2.6) and had the fastest rate of stem elongation (Tables 2.7 and 2.8). Plugs held in the flat for two or four weeks after PPS survived until the end of the study, but stunted severely and were only one third of the height of those transplanted on time. Plugs held for six weeks after PPS died six weeks after transplanting. Plugs held for eight weeks after PPS died in the plug flat before transplanting. Both final height and final diameter of *Tagetes* 'Little Devil Fire' were greatest in plugs transplanted at PPS (Table 2.6). However, plants with the smallest final heights were those held for four and six weeks after PPS; plants with the smallest final diameter were those held for two or four weeks after PPS. Both height and diameter growth rates were fastest in plugs transplanted at PPS Height growth rate was slowest in plugs held for eight weeks after PPS (Tables 2.7 and 2.8). However, these plugs did not have smaller final heights because they were taller than all other treatments at the time of transplanting (Table 2.5).

The remaining species were not negatively affected by being held in the plug flats (Table 2.6, Fig. 2.2). For *Begonia*, *Impatiens* and *Lycopersicon*, height after eight weeks increased with the amount of time plugs were held after PPS. *Eustoma* plants showed no clear relationship between final plant height and amount of time plants were held in the plug flats after PPS. For *Begonia* 'Harmony Pink' final height increased with the amount of time plugs were held in the plug flat after PPS. For example, those held for eight weeks after PPS were tallest by the end of the study (Table 2.6). Diameter showed a similar effect with plugs transplanted at PPS having the smallest diameter and those held for six weeks after PPS having the largest (Table 2.6). Stem elongation rates for *Begonia* were slowest in plugs held for eight weeks after PPS (Tables 2.7 and 2.8). However, since these plugs were taller than all other treatments at the time of transplanting (Table 2.5), slow growth rate did not negatively affect final performance. Diameter growth rates were slowest in plugs transplanted at PPS (Tables 2.7 and 2.8). These plugs also had the smallest diameters of all treatments at transplanting (Table 2.5), which further explains why they were smaller at the end of the experiment. Final heights and diameters of *Eustoma* 'Balboa Purple' were significantly different between treatments, but neither seemed to be affected by the amount of time plugs were held in the plug flat before transplanting. For both height and diameter, no clear relationship occurred between amount of time held in the plug flat after PPS and final height and diameter. For example, plugs transplanted six weeks after PPS were on average taller than any other group of plugs, and those transplanted eight weeks after PPS had the largest final diameter. Both height and diameter growth rates for *Eustoma* were greatest in plugs transplanted at PPS (Tables 2.7 and 2.8), but this failed to make a difference in final measurements because they were smaller than the other treatments at transplanting (Table 2.5). *Impatiens* 'Dazzler Red' plugs held in the plug flat for six or eight weeks after PPS were tallest at the end of the study. Plugs transplanted at PPS had the fastest stem elongation rate of all treatments (Tables 2.7 and 2.8), but because they were smallest at the time of transplanting (Table 2.5), they remained shorter at the end of the study than plugs transplanted six or eight weeks after PPS. Amount of time in the plug flat did not affect final plant diameter or diameter growth rate. The longer *Lycopersicon* 'Heartland' plugs were held in the plug flat after PPS, the taller the final heights, even though plugs transplanted at PPS had the fastest growth rates and those transplanted eight weeks after PPS had the slowest (Table 2.7 and 2.8). It should be noted that the longer plugs were held in plug flats, the taller they were at transplanting (Table 2.5). Final plant diameter was not affected by the treatments, though growth rates of plugs transplanted at PPS were greatest and those held for 8 weeks after PPS were the least (Tables 2.7 and 2.8).

Discussion

Out of the 15 species surveyed, five were negatively effected by being held in plug flats past PPS, including *Callistephus, Celosia, Consolida, Dianthus* and *Tagetes* (Tables 2.2 and 2.6; Fig. 2.1 and 2.2). Similarly, Latimer (1991) found that the final height (7 weeks after transplanting) of *Tagetes* seedlings grown in Todd 080A plug flats (equivalent to 288) was 12% less than those of plants grown in flats with larger cells (Todd 175A). van Iersel et al. (1997) found that *Salvia* plants grown in containers with a volume of 7.3 mL (288 plug flats) had a lower leaf area ratio and dry mass than those grown in larger containers. Both studies indicate that plants grown under greater root volume restriction did not perform as well as those grown without root volume restriction in the flat or after transplanting. It is possible to correlate the amount of time plugs are held in the plug flat after PPS with an increased root volume restriction. Therefore, many of the species used in our survey confirm that increased root volume restriction leads to decreased post-transplant performance. However, our study did not necessarily find that plants held in the plug flat after PPS were smaller than those transplanted at PPS at the time of removal from the plug flat. This can be attributed to excessive stretching occurring in the plug flat, which is caused by the "canopy effect" that occurs in high-density situations. When plants are grown close together, the red:far red ratio is decreased, which causes plants to elongate more rapidly (Ballaré et al., 1995). This also helps explain why faster growth rate did not necessarily lead to larger final size, as seen in *Brassica, Eustoma, Impatiens, Lycopersicon* and *Viola.* Though the growth rates were fastest for plugs of these species transplanted at PPS, they still did not "catch up" in final size to plants that were able to elongate in the plug flat.

Styer and Koranski (1997) indicated that many cut flower species such as *Consolida ambigua* and *Ammi majus* rarely produce high quality stems from plugs but regularly produce long, high quality stems from direct-seeding in the field or greenhouse bed. In our study two out of the three cut flower species surveyed, *Callistephus* and *Consolida*, were unable to produce strong, tall stems if they were held in the plug flat for any amount of time after PPS. This suggests that certain cut flower species can perform well when produced from plugs, but only if they are transplanted on time.

More species in the fall survey were unaffected by the amount of time held in the plug flat than species that were affected. This was probably due to the reduced growing period recorded for the fall survey. Had these plants been allowed to grow as long as those in the spring survey, the results may have been different. Also, had diameter been recorded in the fall survey, other differences may have been brought to light.

Because mixed results were obtained for *Consolida*, further testing needs to be conducted on this species. In the fall survey, we only looked at the growth rate of plugs held for four weeks or less after PPS, whereas in the spring, we used data from plugs held for up to eight weeks after PPS. In addition, the fall survey only analyzed data collected for five weeks after transplanting, whereas in the spring, we analyzed data collected for eight weeks after transplanting. It is also important to note that in the spring a greater amount of plants died before the end of the experiment than in the fall. This could be due to more conducive temperatures for *Consolida*, a cool-season crop, in the fall. Another difference between the two *Consolida* experiments is that in the fall, plugs were grown in a 200 plug flat (11.2 ml), whereas in the spring they were grown in a 288 plug flat (7.3 ml). The roots of plants grown in the fall were not as restricted as those grown in the spring and this may have influenced post-transplant performance.

It should also be noted that an increase in height does not necessarily equal an increase in quality. Though many plants held in the plug flats after PPS were taller at the end of the two studies, these plants were not necessarily sellable. Species such as *Begonia* lacked sufficient branching and were quite spindly when held after PPS, which reduced final plant quality.

Conclusions

Our study confirms that some species are sensitive to the negative effects of being grown in plug flats, including *Callistephus, Celosia, Consolida, Dianthus,* and *Tagetes* and should be transplanted at PPS. While it is best to transplant plugs on time, several species are not as sensitive to the amount of time held in plug flats after PPS. These species include: *Antirrhinum, Brassica, Begonia, Eustoma, Gazania, Impatiens, Lycopersicon, Matthiola* 'Christmas Ruby' and 'Harmony Cherry Blossom', and *Viola*. Hundreds of other species are grown by the floriculture industry and should also be tested. Research also needs to determine the causes of the stunting caused by plug flat holding and methods of overcoming this problem.

Literature Cited

Ballare', C.L., A.L. Scopel, and R. A. Sanchez. 1995. Plant morphogenesis in canopies, crop growth, and yield. HortScience 30:1172-1181.

Latimer, J.G. 1991. Container size and shape influence growth and landscape performance of marigold seedlings. HortScience 26: 124-126.

Styer, R.C. and D.S. Koranski. 1997. Plug and transplant production: a grower's guide. Ball Publishing, Batavia Ill

van Iersel, M. 1997. Root restriction effects on growth and development of salvia. HortScience 32:1186-1190.

Table 2.1. Initial plant height (cm) of seven fall bedding and cut flower species recorded at the time of transplanting from the plug flat to 15-cm pots. Means are an average of data from ten plants.

	No. of weeks held in flat after pullable plug stage (PPS)[z]				
0	**1**	**2**	**3**	**4**	**Significance**
***Antirrhinum* 'Floral Showers Coral Bicolor"**					
1.0 c[y]	4.8 b	5.6 b	4.4 b	9.5 a	0.0001
***Brassica* 'Red Peacock'**					
6.2 b	9.7 a	9.5 a	11.2 a	9.8 a	0.0100
***Consolida* 'Pink Fantasy'**					
2.3 bc	1.9 c	2.9 b	1.8 c	4.3 a	0.0001
***Dianthus* 'Telstar Picotee'**					
4.8 bc	5.8 abc	6.2 ab	4.7 c	6.9 a	0.0150
***Gazania* 'Daybreak Mix'**					
6.1	7.8	7.7	6.4	7.1	NS
***Matthiola* 'Christmas Ruby'**					
8.8 c	10.8 bc	12.9 b	14.3 ab	17.3 a	0.0003
***Matthiola* 'Harmony Cherry Blossom'**					
5.6 b	7.5 ab	7.6 ab	9.0 a	7.7 a	0.0307
***Viola* 'Starlet Rose with Blotch'**					
2.2 c	2.9 bc	2.5 c	5.1 a	3.9 ab	0.0002

[z] PPS = when root ball sufficiently holds together on its own.

[y] Means within rows separated by LSD, $P \leq 0.05$.

Table 2.2. Plant height (cm) of seven fall bedding and cut flower species recorded five weeks after being transplanted from the plug flat to 15-cm pots. Means are an average of data from ten plants.

No. of weeks held in flat after pullable plug stage (PPS)[z]					
0	**1**	**2**	**3**	**4**	**Significance**
***Antirrhinum* 'Floral Showers Coral Bicolor"**					
9.5 b[y]	10.4 b	10.8 ab	10.7 b	12.3 a	0.0124
***Brassica* 'Red Peacock'**					
26.9	25.5	24.8	23.2	25.0	NS
***Consolida* 'Pink Fantasy'**					
15.2 ab	8.5 b	14.8 ab	23.1 a	21.9 a	0.0074
***Dianthus* 'Telstar Picotee'**					
16.8 a	13.8 b	13.0 b	13.0 b	13.7 b	0.0077
***Gazania* 'Daybreak Mix'**					
11.4	11.7	11.3	12.4	14.0	NS
***Matthiola* 'Christmas Ruby'**					
33.1	32.2	32.8	32.0	34.9	NS
***Matthiola* 'Harmony Cherry Blossom'**					
18.9	21.1	12.5	8.9	14.0	NS
***Viola* 'Starlet Rose with Blotch'**					
10.0 bc	9.6 c	9.7 c	11.2 ab	11.4 a	0.0098

[z] PPS = when root ball sufficiently holds together on its own.

[y] Means within rows separated by LSD, $P \leq 0.05$.

Table 2.3. Comparison of height growth rates (slopes) between treatments, using contrast statements in seven fall bedding and cut flower species.

No. of weeks held in flat after pullable plug stage (PPS)[z]			
0 vs. 1,2,3,4	**0, 1 vs. 2,3,4**	**0,1,2 vs. 3,4**	**0,1,2,3 vs.4**
	Antirrhinum		
0.0001	0.0001	0.0001	0.0001
	Brassica		
0.0001	0.0001	0.0003	NS
	Consolida		
NS	0.0001	0.0001	NS
	Dianthus		
0.0001	0.0001	0.0087	0.0290
	Gazania		
NS	NS	0.0042	0.0358
	***Matthiola* 'Christmas Ruby'**		
NS	NS	0.0288	NS
	***Matthiola* 'Harmony Cherry Blossom**		
0.0022	0.0001	0.0001	NS
	Viola		
0.0393	NS	NS	NS

[z]PPS = when root ball sufficiently holds together on its own.

Table 2.4. Slope (growth rate) and intercept estimates for seven fall bedding and cut flower species.

	No. of weeks held in flat after pullable plug stage (PPS)[z]				
	0	**1**	**2**	**3**	**4**
			Antirrhinum		
Slope	1.9	1.2	1.0	1.0	0.5
Intercept	12.1	15.9	17.4	16.5	19.6
			Brassica		
Slope	4.4	3.3	3.0	2.5	3.0
Intercept	18.1	20.5	21.0	21.9	21.9
			Consolida		
Slope	2.5	1.4	2.3	4.1	3.3
Intercept	12.2	12.6	12.5	10.3	12.8
			Dianthus		
Slope	2.5	1.7	1.4	1.6	1.4
Intercept	15.5	16.4	16.5	14.9	17.6
			Gazania		
Slope	1.0	0.8	0.6	1.2	1.3
Intercept	17.4	18.7	18.8	17.6	18.2
			***Matthiola* 'Christmas Ruby'**		
Slope	4.8	4.4	4.3	3.4	3.6
Intercept	16.9	19.0	22.8	24.7	27.5
			***Matthiola* 'Harmony Cherry Blossom'**		
Slope	2.5	2.8	1.1	0.1	1.5
Intercept	15.8	17.7	18.7	20.3	18.8
			Viola		
Slope	1.6	1.4	1.4	1.1	1.5
Intercept	12.1	13.3	13.7	15.7	14.9

[z]PPS = when root ball sufficiently holds together on its own.

Table 2.5. Initial plant height (cm) of eight spring bedding and cut flower species recorded at the time of transplanting from the plug flat to 17-cm pots. Means are an average of data from ten plants.

	No. of weeks held in flat after pullable plug stage (PPS)[z]					
Measurement (cm)	**0**	**2**	**4**	**6**	**8**	**Significance**
			Begonia			
Height	1.0 e[y]	3.9 d	7.7 c	11.9 b	17.1 a	0.0001
Diameter	4.9 c	7.7 b	10.3 a	9.6 a	10.6 a	0.0001
			Callistephus			
Height	3.1 d	6.1 c	10.9 b	14.9 a	--[x]	0.0001
			Celosia			
Height	2.7 d	7.7 c	17.1 b	33.0 a	34.0 a	0.0001
Diameter	5.7 d	11.6 c	18.4 b	20.3 a	20.3 a	0.0001
			Consolida			
Height	3.4	5.0	5.2	5.6	--	NS
			Eustoma			
Height	3.4 e	9.2 d	19.2 c	41.2 b	51.0 a	0.0001
Diameter	5.8 c	7.9 b	6.7 c	9.0 ab	9.3 a	0.0001
			Impatiens			
Height	0.5 d	4.3 c	6.7 b	14.3 a	8.4 b	0.0001
Diameter	5.0 c	7.1 b	8.3 b	13.0 a	14.6 a	0.0001
			Lycopersicon			
Height	1.2 e	11.0 d	21.3 c	37.5 b	44.6 a	0.0001
Diameter	5.9 e	11.5 d	20.9 c	25.1 b	31.1 a	0.0001
			Tagetes			
Height	1.5 d	4.8 c	8.0 b	8.2 b	10.0 a	0.0001
Diameter	5.4 c	9.0 b	11.7 a	8.9 b	9.4 b	0.0001

[z] PPS = when root ball sufficiently holds together on its own.

[y] Means within rows separated by LSD, $P \leq 0.05$.

[x] plants dead

Table 2.6. Plant height and diameter of eight spring bedding and cut flower species recorded eight weeks after transplanted from the plug flat to 17-cm diameter pots. Means are an average of data from ten plants.

	No. of weeks held in flat after pullable plug stage (PPS)[z]					
Measurement (cm)	**0**	**2**	**4**	**6**	**8**	**Significance**
			Begonia			
Height	23.4 d[y]	27.3 c	31.6 b	32.3 b	34.9 a	0.0001
Diameter	33.2 d	36.2 cd	40.8 ab	42.8 a	38.3 bc	0.0001
			Callistephus			
Height	55.1 a	53.4 a	40.0 b	--[x]	--	0.0188
			Celosia			
Height	51.3 a	50.8 a	50.0 ab	45.2 b	45.3 b	0.0440
Diameter	45.5 a	37.4 bc	33.7 c	38.4 b	42.3 ab	0.0032
			Consolida			
Height	60.7 a	20.1 b	18.0 b	--	--	0.0007
			Eustoma			
Height	68.8 b	65.2 b	66.9 b	75.8 a	69.5 ab	0.0385
Diameter	13.2 ab	12.3 bc	11.0 c	12.2 bc	14.3 a	0.0003
			Impatiens			
Height	18.9 c	17.7 c	19.1 c	22.7 b	25.8 a	0.0001
Diameter	52.8	80.6	58.4	60.3	62.8	NS
			Lycopersicon			
Height	75.2 b	79.0 b	89.4 a	88.3 a	93.5 a	0.0012
Diameter	83.4	83.7	81.5	80.9	77.9	NS
			Tagetes			
Height	16.5 a	15.4 ab	13.0 b	13.0 b	14.7 ab	0.0492
Diameter	28.0 a	23.4 cd	21.7 d	25.0 bc	26.5 ab	0.0001

[z]PPS = when root ball sufficiently holds together on its own.

[y] Means within rows separated by LSD, $P \leq 0.05$.

[x]plants dead

Table 2.7. Comparison of height and diameter growth rates (slopes) among treatments, using contrast statements in eight spring bedding and cut flower species.

	No. of weeks held in flat after pullable plug stage (PPS)[z]			
	0 vs. 2,4,6,8	**0,2 vs. 4,6,8**	**0,2,4 vs. 6,8**	**0,2,4,6 vs. 8**
		Begonia		
Height	NS	NS	0.0104	0.0055
Diameter	0.0233	0.0170	NS	NS
		Callistephus		
Height	0.0001	0.0001	0.0001	--[y]
		Celosia		
Height	0.0001	0.0001	0.0001	0.0001
Diameter	0.0001	0.0001	0.0003	NS
		Consolida		
Height	0.0001	0.0001	0.0001	--
		Eustoma		
Height	0.0001	0.0001	0.0001	0.0001
Diameter	0.0001	0.0001	0.0008	NS
		Impatiens		
Height	0.0001	0.0031	NS	0.0198
Diameter	NS	NS	NS	NS
		Lycopersicon		
Height	0.0008	0.0001	0.0001	0.0001
Diameter	0.0005	0.0001	0.0002	0.0033
		Tagetes		
Height	0.0001	0.0001	0.0001	0.0010
Diameter	0.0001	0.0007	NS	NS

[z]PPS = when root ball sufficiently holds together on its own.

[y]Plants died in plug flat before transplanting.

Table 2.8. Slope (growth rate) and intercept estimates for eight spring bedding and cut flower species.

	No. of weeks held in flat after pullable plug stage (PPS)[z]				
	0	**2**	**4**	**6**	**8**
			Begonia		
			Height		
Slope	2.9	3.1	3.2	2.8	2.5
Intercept	-0.7	1.9	5.0	9.9	14.9
			Diameter		
Slope	3.6	3.8	4.0	4.4	3.7
Intercept	4.2	6.6	8.3	8.7	10.0
			Callistephus		
			Height		
Slope	6.5	6.8	5.6	1.3	--[y]
Intercept	-5.4	0.5	9.3	15.6	--
			Celosia		
			Height		
Slope	6.7	5.7	3.9	1.5	1.6
Intercept	-0.2	8.6	21.6	32.5	32.3
			Diameter		
Slope	5.2	3.2	1.9	2.3	2.7
Intercept	10.4	16.6	20.3	18.9	16.9
			Consolida		
			Height		
Slope	7.8	2.0	1.7	1.0	--
Intercept	-3.6	4.4	6.4	6.0	--

Table 2.8 (continued)

			Eustoma		
			Height		
Slope	8.7	7.7	6.2	4.4	2.4
Intercept	-3.4	7.0	23.3	43.0	51.4
			Diameter		
Slope	1.0	0.6	0.5	0.4	0.6
Intercept	5.8	7.4	7.7	9.8	9.7
			Impatiens		
			Height		
Slope	2.3	1.7	1.4	1.1	2.1
Intercept	0.1	5.5	7.2	11.8	7.6
			Diameter		
Slope	6.1	9.0	6.7	6.2	6.3
Intercept	5.0	2.8	8.9	11.8	10.5
			Lycopersicon		
			Height		
Slope	9.6	9.2	8.9	9.2	6.5
Intercept	-0.9	10.1	20.2	36.0	43.5
			Diameter		
Slope	10.1	9.3	7.8	7.4	6.7
Intercept	15.9	20.4	28.0	28.6	31.3
			Tagetes		
			Height		
Slope	1.7	1.3	0.7	0.6	0.6
Intercept	3.8	5.6	7.8	7.7	9.1
			Diameter		
Slope	2.8	1.8	1.3	2.1	2.1
Intercept	8.7	11.6	11.8	8.7	9.5

[z]PPS = when root ball sufficiently holds together on its own.

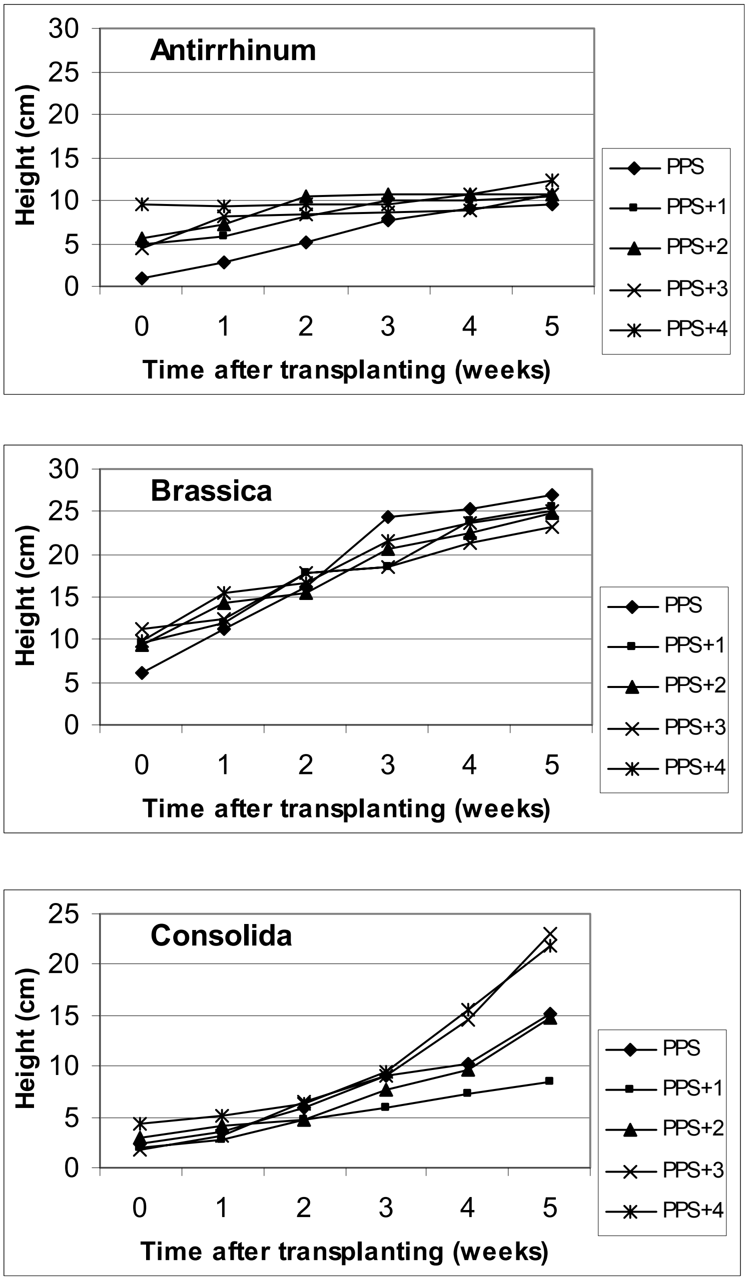
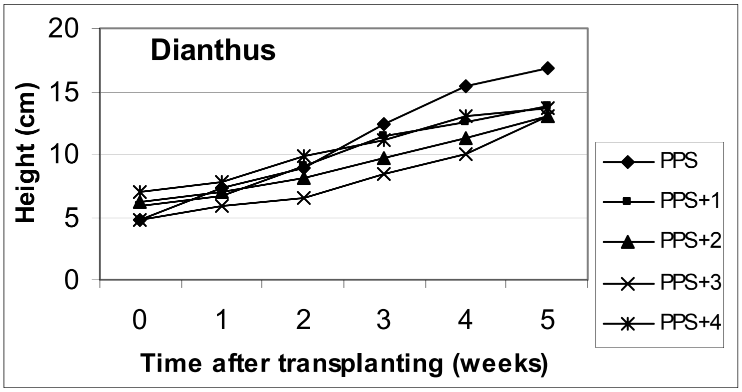


Fig. 2.1. Influence of 1, 2, 3, or 4 weeks additional production time in a plug flat on eight bedding plant and cut flower species. Plugs at PPS were transplanted at the pullable plug stage. Plugs at PPS+X were held in the plug flat for X weeks after PPS. Means are an average data from ten plants.



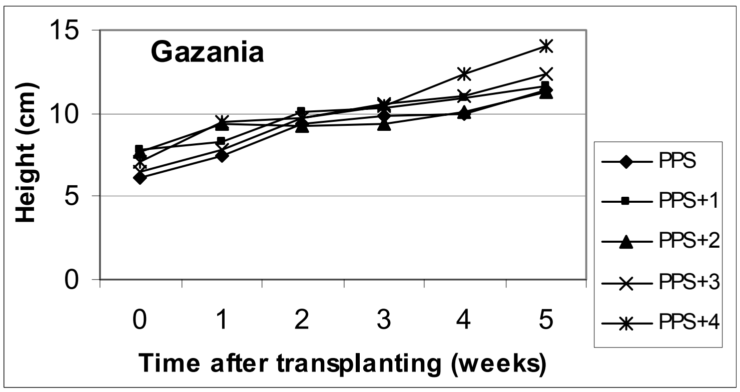
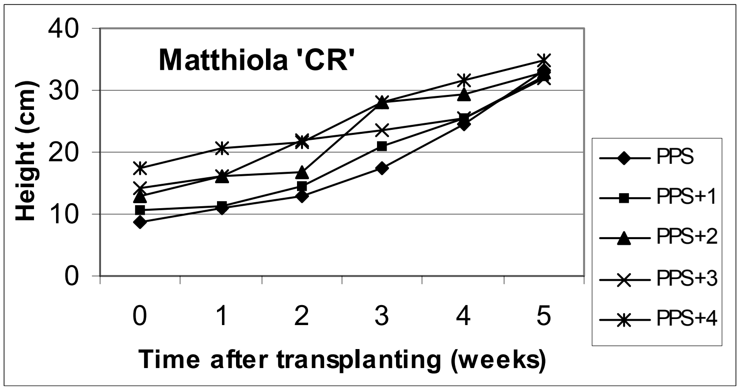
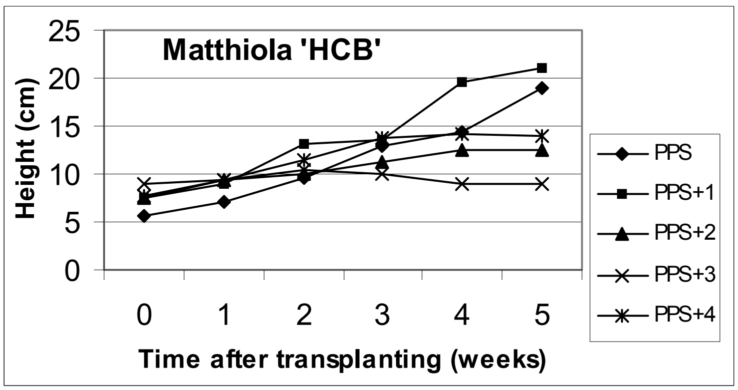


Fig. 2.1 (continued). Influence of 1, 2, 3, or 4 weeks additional production time in a plug flat on eight bedding plant and cut flower species. Plugs at PPS were transplanted at the pullable plug stage. Plugs at PPS+X were held in the plug flat for X weeks after PPS. Means are an average data from ten plants.





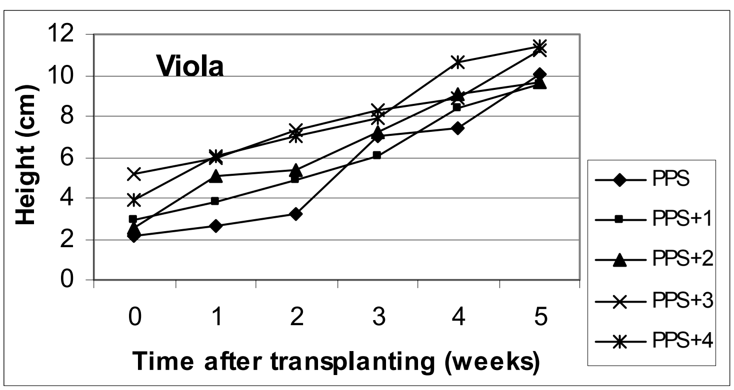
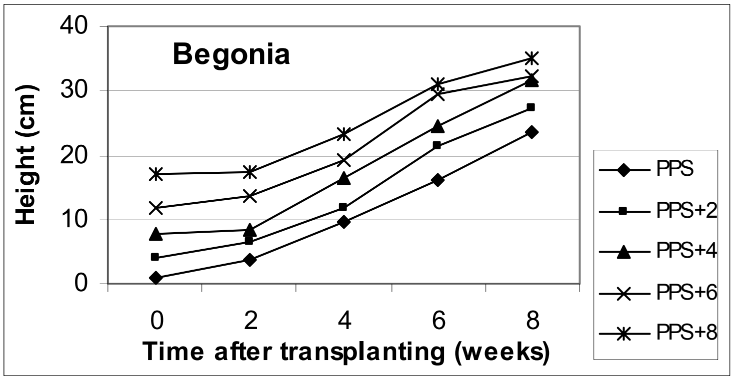
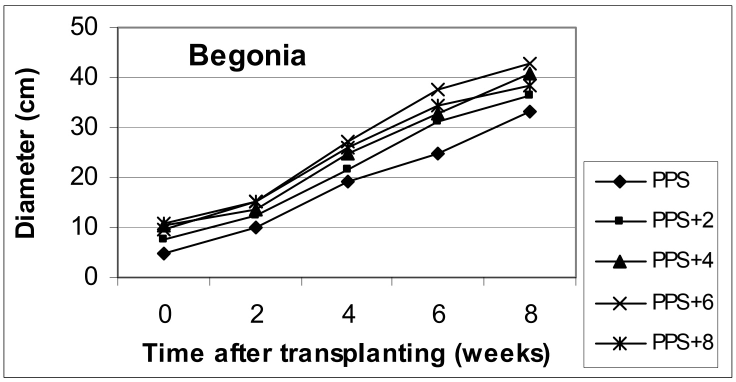


Fig. 2.1 (continued). Influence of 1, 2, 3, or 4 weeks additional production time in a plug flat on eight bedding plant and cut flower species. Plugs at PPS were transplanted at the pullable plug stage. Plugs at PPS+X were held in the plug flat for X weeks after PPS. Means are an average data from ten plants. Matthiola CR = Matthiola 'Christmas Ruby'. Matthiola HCB = Matthiola 'Harmony Cherry Blossom'.





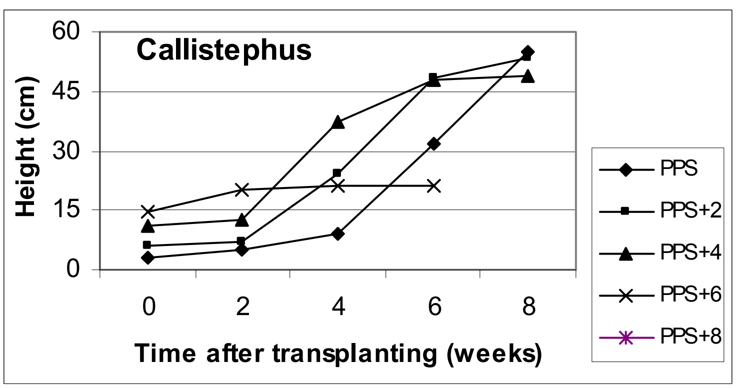
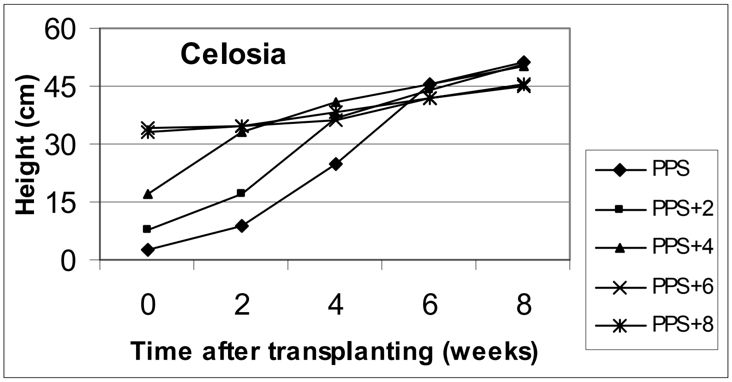
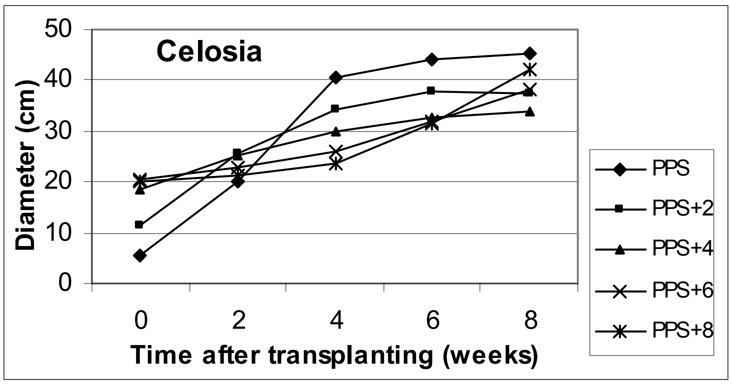


Fig. 2.2. Influence of 0, 2, 4, 6, or 8 weeks additional production time in a plug flat on seven bedding plant and cut flower species. Plugs at PPS were transplanted at the pullable plug stage. Plugs at PPS+X were held in the plug flat for X weeks after PPS. Means are an average data from 10 plants.





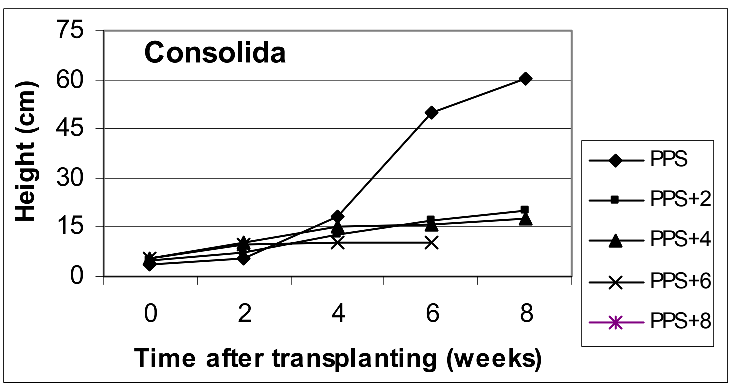
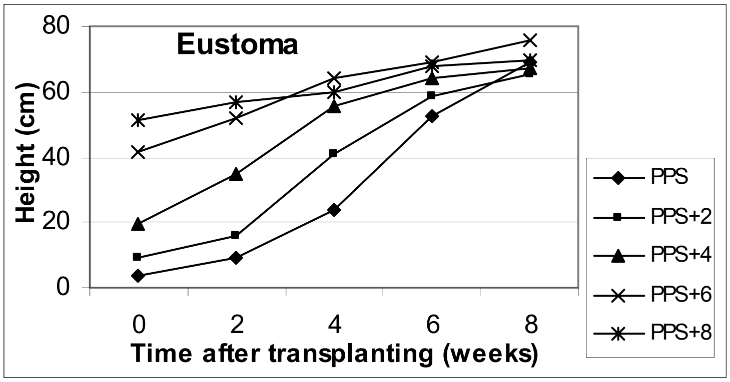
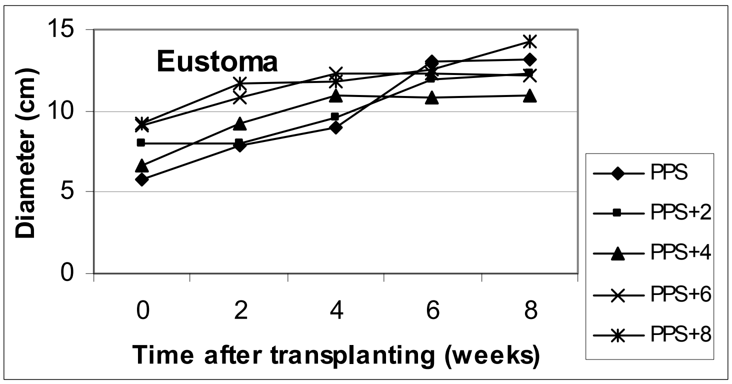


Fig. 2.2 (continued). Influence of 0, 2, 4, 6, or 8 weeks additional production time in a plug flat on seven bedding plant and cut flower species. Plugs at PPS were transplanted at the pullable plug stage. Plugs at PPS+X were held in the plug flat for X weeks after PPS. Means are an average data from 10 plants.





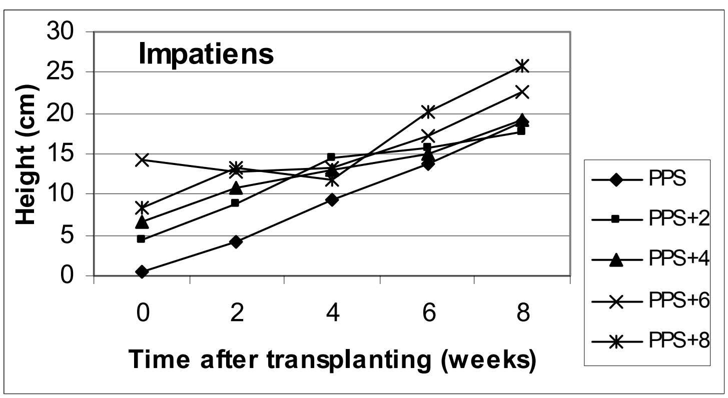
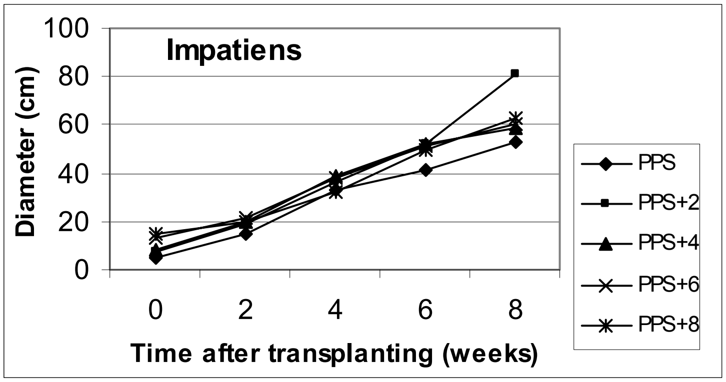
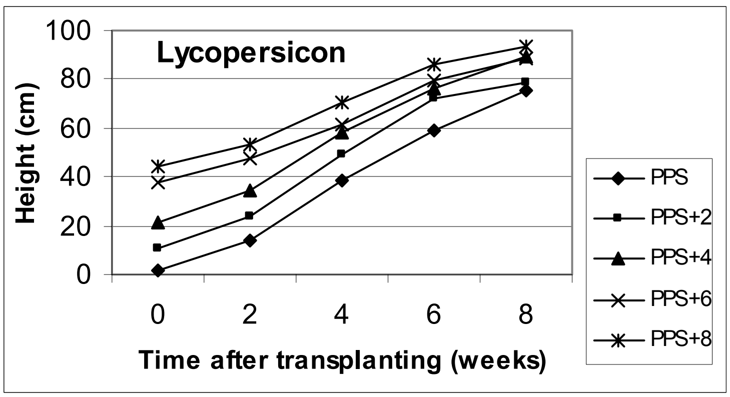


Fig. 2.2 (continued). Influence of 0, 2, 4, 6, or 8 weeks additional production time in a plug flat on seven bedding plant and cut flower species. Plugs at PPS were transplanted at the pullable plug stage. Plugs at PPS+X were held in the plug flat for X weeks after PPS. Means are an average data from 10 plants.





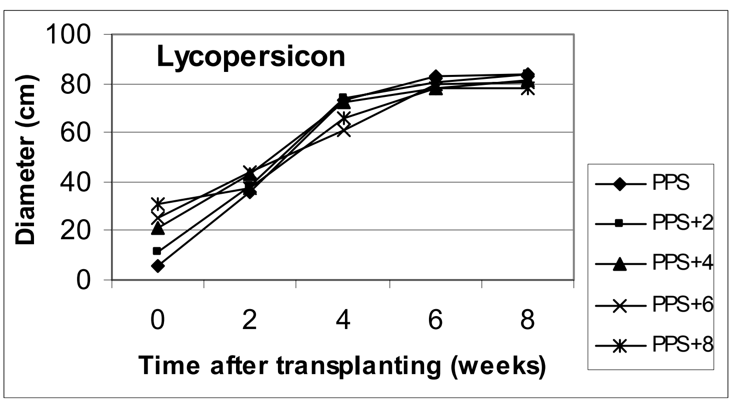
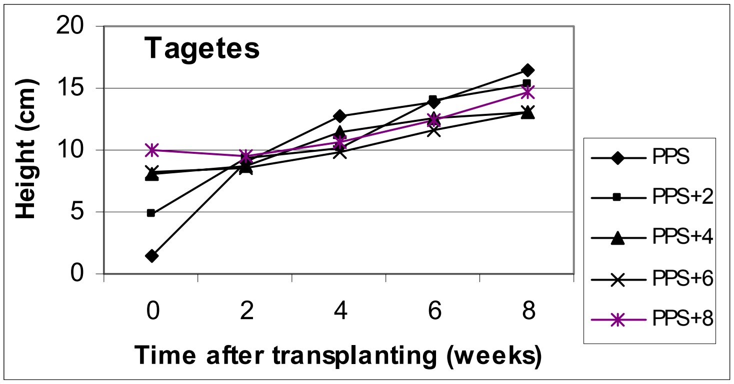


Fig. 2.2 (continued). Influence of 0, 2, 4, 6, or 8 weeks additional production time in a plug flat on seven bedding plant and cut flower species. Plugs at PPS were transplanted at the pullable plug stage. Plugs at PPS+X were held in the plug flat for X weeks after PPS. Means are an average data from 10 plants.



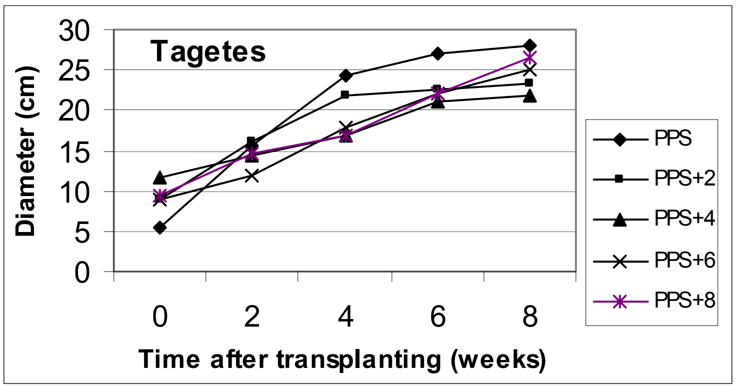


Fig. 2.2 (continued). Influence of 0, 2, 4, 6, or 8 weeks additional production time in a plug flat on seven bedding plant and cut flower species. Plugs at PPS were transplanted at the pullable plug stage. Plugs at PPS+X were held in the plug flat for X weeks after PPS. Means are an average data from 10 plants.

CHAPTER III

PREVENTION OF POST-TRANSPLANT STUNTING OF PLANTS GROWN IN PLUG FLATS

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Additional index words. Plug flat, bedding plants, cut flowers, stunting, transplants, seedlings, growth rate, pullable plug stage (PPS).

Abstract. Plugs should be transplanted at the pullable plug stage (PPS), which occurs when the root ball holds together after removal from the plug flat. If seedlings are held in plug flats for too long after PPS, they may not return to a normal growth rate after transplanting. This can be due to several factors including nutrient deficiency, hormone deficiency, low oxygen availability, water stress, light quality and quantity, the root hitting the edge of the container and the inability of rootballs to expand once

transplanted. Seed of *Catharanthus* L. 'Pacifica Lilac' and/or *Celosia* L. 'Century Red' or 'Century Fire' were sown into 288 size (7.3 ml) plug flats. Plants were subjected to various plug flat treatments to 1) help determine the cause of plug stunting and 2) examine methods of overcoming plug stunting and the inability of plants to regain a normal growth rate after transplanting. These treatments included pre-transplant nitrogen application (*Celosia* 'Century Red'), pre-transplant gibberellic acid application (*Catharanthus* 'Pacifica Lilac' and *Celosia* 'Century Fire'), root obstruction (*Catharanthus* 'Pacifica Lilac' and *Celosia* 'Century Fire'), pretransplant root ball disturbance (*Catharanthus* 'Pacifica Lilac' and *Celosia* 'Century Fire'), and growing plugs in flats with longer drainage columns (*Catharanthus* 'Pacifica Lilac' and *Celosia* 'Century Fire'). Each experiment included at least one treatment plug flat and a control plug flat. In addition, four of the experiments included a control with seeds sown directly into 17 cm (1.66 L) pots. In the three completed experiments containing a direct seeded control, plants directly sown into 17 cm (1.66 L) pots were larger than both control and treated plugs. This suggests that direct seeding is the fastest way to produce high quality plants. The only treatment that made any consistent difference in post-transplant growth was growing plugs on a longer drainage column. Growing plugs on a longer drainage column led to a larger final diameter in *Celosia* 'Century Fire' plugs that were transplanted on time. This leads us to believe that low oxygen availability could be a cause of plug stunting and the inability to regain a normal growth rate after transplanting.

Introduction

With some species, plants left in plug flats for too long exhibit premature flowering, apical dominance, and stunting (Latimer, 1991; van Iersel, 1997). These symptoms may be due to several factors including limitations in nutrient uptake, hormone deficiency, water stress, light quantity and/or quality, the root hitting the edge of the container, inability of the rootball to expand after transplanting, and low oxygen availability.

Limitations in nutrient uptake may cause stunt plants grown in plug flats and prevent a normal growth rate after transplanting. According to van Iersel et al. (1998; 1999), the amount of nutrient received by plugs is often not sufficient for pre- or post-transplant growth. The recommended fertilizer nitrogen concentration for plugs, 3.5 to 11 mM once or twice weekly (Styer and Koranski, 1997), was too low for successful plug growth rates after transplanting *Catharanthus, Impatiens* Hook. F.*, Petunia* (Hook.) Schinz & Thellung, and *Salvia* L. plugs. van Iersel et al. (1998) found that the greatest post-transplant growth occured when 16 to 32 mM nitrogen was used on *Impatiens* and *Petunia* plugs. In *Catharanthus* and *Salvia* plugs, pre- and post-transplant growth was linearly correlated with increasing N concentration from 8 mM to 32 mM (van Iersel et al., 1999). In addition, phosphorus and potassium fertilizer levels were not as important to the successful growth of plugs after transplanting (van Iersel et al., 1998; 1999).

Hormone deficiency has been examined in many studies as a possible cause of plug stunting. The restricted root zone volume of the plug flat may cause plants to produce lower amounts of hormones, namely gibberellins (GA) and cytokinins, necessary for normal growth and development (Dubik et al., 1989; Carmi and Heuer, 1980; Ismail and Noor, 1996). A decrease in the transport of GA and cytokinins from the roots to the shoot leads to a reduction in shoot growth. Gibberellins are synthesized in the roots and are responsible for shoot elongation. Cytokinins are also synthesized in the roots and promote cell division. An increase in the presence of abscisic acid (ABA), a growth inhibitor, has also been hypothesized (Liu and Latimer, 1995). Abscisic acid helps plants respond to physiological stress by inhibiting growth. For example, Liu and Latimer (1995) determined that root restriction increased levels of absisic acid produced by the roots in *Citrullus lanatus* (Thunb.) Matsumura & Nakai seedlings. The ABA was transported to the shoots via xylem sap, where it inhibited shoot growth. Higher absisic acid levels were measured in the roots of seedlings grown in smaller plug sizes than larger ones. Carmi and Heuer (1980) were able to overcome the stunting of *Glycene max* L. seedlings grown under root zone restriction with the application of GA and benzyladenine, a cytokinin. Therefore, they concluded that a reduction in transport of GA and cytokinins to the shoot from the root was responsible for the stunting of plants grown under rooting volume restriction.

Another possibility for the stunting of plugs is low oxygen availability. If oxygen is not available to the roots, root respiration is significantly reduced, affecting other metabolic processes within the plant. Responses to low oxygen availability are similar to those caused by soil compaction, waterlogging, and limited aeration including reduced leaf growth, epinasty, root death, reduced branching, and lower transpiration levels (Peterson et al., 1991). The high-density root environments of small containers increase the competition for oxygen. For example, in small volume containers more of the soil pore space is occupied by roots than in larger containers. Increasing root density increases competition for resources and severely limits the oxygen supply to the inner roots (Peterson et al., 1991). Peterson et al. (1991) also reported that new roots tend to develop close to the source of nutrients and oxygen. In doing so, they form a barrier to the oxygen supply for other roots in the containers, therefore restricting the amount of oxygen available to the rest of the roots. Dubik et al. (1989) also suggest that poor aeration could be a cause for the alteration in shoot growth in plants grown in restricted root volume. They hypothesize that poor aeration affects the oxygen available to all roots because of reduced surface area for air exchange, limited physical space within the container available for gas exchange, and increased effects of compaction due to settling of the medium, which would be more likely to occur in small containers than in large ones.

Water stress may also stunt plants grown with restricted rooting volumes. Many studies have shown that even when water is not limited, plants grown in small containers demonstrate drought stress symptoms (Hameed et al., 1987; Kharkina et al., 1999). These symptoms include smaller leaf area, thicker leaves, wilting in the afternoon, and decreased transpiration rate (Hameed et al., 1987). Kharkina et al. (1999) suggested that the reason for drought stress symptoms in root restricted plants is the inability of roots to absorb and transport water due to the physical limitation of root volume in relation to the size of the shoots. Inability to absorb water may also be due to the decrease in root hair initiation and formation of lateral roots (Krizek et al., 1985). Hanson et al. (1987) found that plants grown under conditions of root restriction demonstrated reduced root pressure, which led them to assume that the plants were under some water stress, though the plants had been adequately watered. In contrast, many studies have shown that water stress is not apparent if plants are irrigated frequently (Krizek et al., 1985; Carmi and Heuer, 1980; Ismail and Noor, 1996; Peterson et al., 1991). Krizek et al. (1985) indicated that leaf water potentials, stomatal conductance, assimilate distribution, carbohydrate concentration, nitrogen concentration, and other factors differ between plants subjected to soil moisture stress and restricted root zone volume. Other studies show that while water stress is a factor, it is probably not the most important factor in the stunting of plants grown in small containers (van Iersel, 1997). Water stress can also be caused by the presence of concentrated amounts of soluble salts in the media. When this occurs, the plant is unable to absorb sufficient water, because the water potential is greater in the media water solution than in the root and more energy is needed for water uptake.

Both light quality and quantity are possible causes of the negative effects of holding plugs for too long in flats. Plant tissue absorbs almost all red light and reflects or transmits most far-red light. When plants are grown in high density situations, such as plug flats, a “canopy effect” occurs. Once the canopy closes, only the leaves at the top of the canopy have access to red light, which they absorb. The remaining leaves receive mostly far red light, which causes stem elongation, reduced branching, and premature flowering (Ballaré et al., 1995). Plants can sense the proximity of other plants due to far-red light reflected off neighboring plants even before the canopy closes (Davis and Simmons, 1994). *Hordeum vulgare* L. plants grown in close proximity to other *Hordeum vulgare* plants exhibited an earlier transition to reproductive growth and fewer main shoot leaves than plants grown in less dense situations.

Light quantity considers the amount of light received by a plant. In plug flats, the seedlings often shade each other, reducing the amount of light available to each seedling. NeSmith (1993) determined that photosynthetically active radiation (PAR) was more of a limiting factor than root restriction in the dry weight accumulation of *Cucurbita moschata* (Duchesne ex Lam.) Duchesne ex Poir., and that the plants seemed to be more sensitive to low levels of PAR than to root restriction.

Other possible causes include the root hitting the container and the inability of a root-bound rootball to expand after transplanting. Rootballs that have been in small containers for long amounts of time may become root-bound and have trouble expanding after transplanting. Gouin (1984) states that root-bound plants are slow to establish and more susceptible to drought stress because their roots continue to grow in a circular manner after transplanting and expand into the soil very slowly. The longer the plant is held in a container, the worse these symptoms become. In the nursery industry, it is recommended that root-bound plants be root pruned to stimulate root branching and help them establish more quickly in the landscape (Gouin, 1984). Root pruning can be either mechanical or chemical. Mechanical root pruning involves slashing the root ball at various points, while chemical root pruning uses a chemical (usually a copper compound) to help roots avoid the container surface. However, though mechanical pruning has been long recommended, Arnold (1996) found that mechanically pruned *Quercus shumardii* Buckl. plants experienced more water stress just after transplanting than plants that were chemically pruned or not pruned at all. Struve (1993) found that there was no difference in height after three years between *Acer rubrum* L., *Liquidambar styraciflua* L., *Quercus rubra* L., and *Quercus coccinea,* Muenchh. plants that had been root pruned and those that had not.

The objectives of this experiment were 1) to determine possible causes of stunting due to plugs being held too long after PPS and 2) to examine methods of overcoming plug stunting and the inability of plants to return to a normal growth rate after transplanting. Methods tested included pre-transplant nitrogen application, pre-transplant gibberellic acid application, obstructing the roots in each plug cell, pre-transplant rootball disturbance, and growing plugs in flats with longer drainage columns.

Materials and Methods

Unless otherwise indicated, seed of *Catharanthus* L. 'Pacifica Lilac' and *Celosia* L. 'Century Fire' were sown in 288 size plug flats (7.3 mL/cell) filled with a peat-based commercial growing substrate (Fafard 4P, Conrad Fafard, Inc. Agawam, Mass.). When recorded, plant height was measured from the top of the pot to the highest point on the plant and diameter was the average of two measurements, one perpendicular to the other. Unless otherwise indicated, plant height and diameter data were collected every other week for nine weeks beginning at the date of transplanting. Data were analyzed using the general linear model procedure (SAS Institute, Cary, N.C.). Least significant difference (LSD) was used for mean separation between treatments. Differences in growth rates were calculated using contrast statements comparing slopes between treatments.

Nitrogen application. Nitrogen drenches from ammonium nitrate at 0, 200, or 400 ppm were applied to *Celosia* 'Century Red' seedlings approximately one week before PPS. At PPS, plugs were transplanted into 17 cm (1.66 L) pots and placed in a completely randomized design with 10 single plant replications (pots) per treatment. Height was recorded weekly for five weeks.

Gibberellic acid (GA) concentration. Gibberellic acid (ProGibb 4%, Abbot Laboratories, North Chicago, Ill.) at 0, 100, 200, and 400 ppm was applied to *Catharanthus* 'Pacifica Lilac' and *Celosia* 'Century Fire' seedlings one week before transplanting. Ten randomly selected plugs from each treatment were transplanted to 17 cm (1.66 L) pots at one and three weeks after addition of GA and placed in a completely randomized design with 10 single plant replications (pots) per treatment. *Celosia* plants were grown in a greenhouse with an average daily temperature of 70.1°F. *Catharanthus* plants were grown in a greenhouse with an average daily temperature of 72.1°F.

Gibberellic acid (GA) application time. Gibberellic acid (ProGibb 4%, Abbot Laboratories, North Chicago, Ill.) at 400 ppm was applied to *Catharanthus* 'Pacifica Lilac' and *Celosia* 'Century Fire' plugs two weeks before transplanting, one week before transplanting, or two weeks before transplanting and again one week before transplanting. An untreated control was also included. Ten randomly selected plugs from each treatment were transplanted into 17 cm pots (1.66 L) at two and four weeks after the first treatment was applied. Plants were grown in a greenhouse with an average daily temperature of 78.6°F.

Root obstruction. One flat of *Catharanthus* 'Pacifica Lilac' seedlings were grown in plug cells partially divided vertically by a plastic insert, to increase the amount of surface area obstructing the roots without reducing media aeration. The other flat contained undivided plug cells. A direct seeded control was also sown into 17 cm (1.66 L) pots (ten pots per species) filled the same growing medium used in the plug flats. At PPS or two weeks after PPS, ten randomly selected plugs from each flat were transplanted into 17 cm (1.66 L) pots. A completely randomized design was used with 10 single plant replications (pots) per treatment. Plants were grown in a greenhouse with average daily temperatures of 76.8°F.

Root ball disturbance. At PPS and two weeks after PPS, twenty randomly selected *Catharanthus* 'Pacifica Lilac' and *Celosia* 'Century Fire' plugs were transplanted from the plug flats into 17 cm (1.66 L) pots. Ten plugs had their root balls manually teased apart before transplanting. The other ten plugs were transplanted without having the root balls disturbed. A direct seeded control was also sown into 17 cm (1.66 L) pots (ten pots per species) filled the same growing medium used in the plug flats. Plants were placed in a completely randomized design with 10 single plant replications per treatment. In *Celosia*, a third group of plugs had their root balls manually teased apart before transplanting four weeks after PPS. *Celosia* plants were grown in a greenhouse with average daily temperatures of 70.1°F. *Catharanthus* plants were grown in a greenhouse with average daily temperatures of 76.8°F.

Longer drainage column. One flat each of *Catharanthus* 'Pacifica Lilac' and *Celosia* 'Century Fire' was grown on top of an open flat of media in an effort to lengthen the drainage column and increase media aeration. A layer of thin, gauze-like fabric was placed at the bottom of the plug flat to prevent roots from growing into the flat of media below. A control flat was also grown without the flat of media underneath. For *Catharanthus,* a direct seeded control was also sown into 17 cm (1.66 L) pots filled with the same medium as used in the plug flats. At PPS and two weeks after PPS, ten randomly selected plugs from each flat were transplanted into 17 cm (1.66 L) pots and placed in a completely randomized design, along with the direct seeded plants in *Catharanthus*, with 10 single plant replications per treatment. *Celosia* plants were grown in a greenhouse with average daily temperatures of 70.2°F. *Catharanthus* plants were grown in a greenhouse with average daily temperatures of 73.9°F. Quality ratings, fresh and dry weights, root area, and root length of plugs were recorded for *Catharnthus*. Plug quality ratings ranged from 0 to 7, with 0 being a dead plug, 3 being a plug with roots constituting less than 10% of the rootball, 5 being an "ideal" plug at PPS (with roots constituting 25 to 50% of the rootball) and 7 being an extremely overgrown plug (with roots constituting over 75% of the rootball). Root area and root length were measured using a Monochrome AgVision System 286 Image Analyzer (Decagon Devices, Inc., Pullman, Wash.)

Results and Discussion

Nitrogen application.

Final height, final diameter, height growth rate and diameter growth rate were unaffected by nitrogen concentration (data not presented). van Iersel et al. (1998) found that increased nitrogen concentrations (16 to 32mM) led to more rapid post-transplant growth in *Impatiens* and *Petunia*. However, van Iersel et al. (1998) applied nitrogen weekly for a period of five weeks, while we applied nitrogen only once a week before transplanting. van Iersel et al. (1999) found that increased nitrogen concentration increased pre-transplant *Catharanthus* and *Salvia* shoot growth. Root and shoot dry mass were positively correlated with pre-transplant nitrogen concentration in the fertilizer for both *Catharanthus* and *Salvia*. Our study only measured height and diameter, which do not account for shoot size in its entirety. Further data collection, such as fresh and dry weights may have yielded more clear-cut results. Though previous research shows that nutrient deficiency could be a cause of plug stunting (van Iersel et al., 1998;1999), our study focused on the use of nitrogen to overcome stunting from other causes. However, had nitrogen deficiency been the cause, it seems logical that the addition of nitrogen would lead to increased post-transplant growth.

Gibberellic acid concentration.

Catharanthus. Plugs that did not receive any GA and were transplanted on the second transplant date had final diameters larger than all other treatments except plugs that received 400 ppm GA and were transplanted at PPS (Table 3.1). Neither GA concentration nor the transplant date alone had any significant effect on final height or diameter. The diameter growth rate for plugs transplanted on the second transplant date was greater than that of plugs transplanted on the first transplant date (Fig. 3.1). Stem elongation rate was unaffected by transplant date (data not presented). Both height and diameter growth rates were unaffected by GA application (data not presented).

*Celosia***.** Both transplant date and GA concentration had a significant effect on final height (Table 3.1). All plugs transplanted on the first transplant date (regardless of GA concentration), along with plugs that received 0 ppm GA were taller than all other treatments but plugs that received 100 ppm and were transplanted on the second transplant date (Table 3.1). Transplant date had a greater effect on final height than GA concentration. Height growth rate of plugs treated with no GA was greater than that of plugs treated with 100 ppm GA (Fig. 3.2). Diameter growth rate of plugs treated with 0 ppm GA was greater than that of plugs treated with 400 ppm GA (Fig. 3.2). Plugs transplanted on the second transplant date elongated faster than those transplanted on the first transplant date (Fig. 3.3). Diameter growth rate was unaffected by transplant date (data not presented).

For both species, there was not an instance in which the final height and diameter were both affected by GA concentration. In *Celosia,* plugs that were transplanted on time were taller by the end of the study (Table 3.1). This suggests that transplanting plants at PPS is more crucial to final plant performance than GA addition.

Gibberellic acid application time.

Catharanthus. Final height and diameter were not affected by GA, transplant date, or an interaction of the two (data not presented). The growth rate for control plugs (regardless of transplant date) was higher than for plugs that received GA two weeks before PPS (Fig. 3.4). Height growth rate was greater in plants transplanted on the first transplant date than those transplanted on the second (Fig. 3.5). Diameter growth rate was unaffected by transplant date (data not presented).

Celosia. Final plant height was not significantly affected by GA, transplant date or an interaction of the two (data not presented). Plugs transplanted on the first transplant date had greater final diameters that were on average 5.4 cm larger than those transplanted later. Plugs transplanted closer to PPS had a faster growth rate for both height and diameter than those transplanted later (Fig. 3.6). Neither height nor diameter growth rate was affected by treatment (data not presented).

In *Catharanthus*, height and diameter growth rates were greater in plants that received 0 ppm GA than those that received GA two weeks before transplanting began (Fig. 3.4). For both species, neither final height nor diameter was affected by treatment and only final diameter in *Celosia* was affected by transplant date. Height growth rates for both species and diameter growth rate for *Celosia* was greatest in plants transplanted at PPS (Figs. 3.5, 3.6). As with the previous experiment, transplanting plugs on time is more important for final plant performance than GA application.

The results obtained in this study differ greatly from the findings of Carmi and Heuer (1981). In their work, exogenous application of gibberellic acid (GA) helped dwarf soybean plants overcome stem reduction completely. In our experiment, GA application did not produce plants larger than those that did not receive any GA. Interestingly enough, Carmi and Heuer (1981) obtained their results using a maximum of 10 ppm of GA, whereas our experiment used a maximum of 400 ppm. However, in their experiment, they used *Hordeum vulgare* (soybean), which may have different physiological properties than *Catharanthus* and *Celosia*. More importantly, their study only measured stem length at 4 and 8 days after the application of the growth hormone (applied when plants were sixteen days old). Conversely, our study measured height for at least nine weeks after the hormone application, which was applied when plants were at least 8 weeks old.

Results of our study indicate that a reduction in transport of gibberellic acid from the root to the shoot is probably not the cause for the stunting that occurs with root-restricted plants. Some studies hypothesized that either an increase in production of ABA (Liu and Latimer, 1995) or a reduction in transport of cytokinins from root to shoot (Dubik, et al., 1989;) was responsible for root restriction induced stunting. Since gibberellic acid, a growth hormone, made very little difference in plant growth, it is unlikely that stunting is caused by abscisic acid (ABA), a growth inhibitor, as GA addition should have been able to overcome the effects caused by ABA. However, cytokinins were not used in our study. Carmi and Heuer (1981) had the greatest stem length increase with plants treated with a combination of GA and cytokinin.

Root obstruction.

Catharanthus. Plants direct seeded into 17 cm (1.66 L) pots were larger at the end of the experiment than all other treatments (Table 3.2). There was no difference in final height or diameter between plugs grown in a root-obstructed flat and those grown in the control flat. Neither final height nor diameter was significantly affected by transplant date and no interaction occurred between treatment and transplant date (Table 3.2). The stem elongation rate of root obstructed plants was greater than that of direct seeded plants and plants transplanted from the control flat (Fig. 3.7). Since root obstructed plants were about 5.1 cm smaller than control plants ($P \leq 0.05$) at transplanting, it is only logical that the stem elongation rate would have to be greater in order for there to be no significant difference in final size between root obstructed and control plugs. Diameter growth rate of direct seeded plants was greater than for all other treatments (Fig. 3.7). There was no difference in diameter growth rate of plugs grown in the root obstructed flat vs. the control flat. Plugs transplanted at PPS had faster stem elongation rates than those that were held past PPS (Fig. 3.8). Diameter growth rate was not affected by transplant date (data not presented).

Results of this experiment indicate that providing more surface area for roots to make contact with caused plugs to be smaller at transplanting. However, root obstructed plugs were not any smaller than those grown without root obstruction after nine weeks. This indicates that root obstruction is helpful in reducing the stretching and legginess that often occurs with overgrown plugs without negatively affecting final size. These results also indicate that post-transplant stunting in root-restricted plants is not caused simply by roots making contact with the edge of the container.

Root ball disturbance

Catharanthus. Direct seeded plants had greater final heights and diameters than any other treatment (Table 3.3). There was no difference in final height and diameter between plants that had their root ball disturbed before transplanting and those that did not (Table 3.3). Height growth rates for all treatments were the same (data not presented), but diameter growth rate of direct seeded plants was greater than plants with disturbed rootballs (Fig. 3.9). Diameter growth rates of plants with disturbed rootballs and those without them did not differ (data not presented). Plugs transplanted close to PPS grew faster (Fig. 3.10) than those transplanted later. Transplant date had no effect on diameter growth rate (data not presented).

Celosia. Final plant height and diameter were greatest in plants that were direct seeded (Table 3.3). Plants transplanted on the first transplant date were taller after nine weeks than those transplanted on the second or third transplant dates. However, they were still not as tall as the direct seeded plants (Table 3.3). Final diameters were greater for plants that did not have their root balls teased and were transplanted on the first transplant date (Table 3.3). Height growth rate was greatest in direct seeded plants (Fig. 3.11) and there was no significant difference between plants with or without root ball disturbance (data not presented). Diameter growth rates were unaffected by treatment (data not presented). Height growth rate was greater in plugs transplanted on the first transplant date than plugs transplanted on the second or third (Fig. 3.11). Diameter growth rates were unaffected by transplant date (data not presented).

Gouin (1984) states that root-bound plants are slow to establish and more susceptible to drought stress because their roots continue to grow in a circular manner after transplanting and expand into the soil very slowly. Thus, he recommends that root-bound plants be mechanically root pruned to stimulate root branching and help them establish more quickly in the landscape (Gouin, 1984). Mechanical root pruning involves slashing the root ball at various points. The root ball disturbance method used in this experiment was very similar to mechanical root pruning in nursery crops, but fewer roots were lost in the process. Struve (1993) found that there was no significant difference in height after three years between *Acer rubrum* L., *Liquidambar styraciflua* L., *Quercus rubra* L., and *Quercus coccinea* Muenchh. plants that had been root pruned and those that had not. Our findings confirm this. Though final height and diameter were greatest in direct seeded plants, plugs with disturbed rooballs were not consistently larger after nine weeks than those without disturbed rootballs. In the nursery industry, some studies (Struve, 1993 and Arnold, 1996) are finding that chemical root pruning, using a copper compound to prevent roots from circling, yields better post-transplant growth than mechanical pruning. Incorporating chemical root pruning into our experiment may have generated more dramatic results.

Longer drainage column.

Catharanthus. Shoot dry weight was greatest in plugs grown on a longer drainage column and transplanted on the second transplant date (Table 3.5). Control plugs transplanted on the second transplant date had greater dry weights than all other treatments (Table 3.5). Both root area and root lengths were greatest in plugs transplanted on the second transplant date (Table 3.5). This is to be expected as plugs transplanted later had more time to develop a root system. Plug quality ratings and shoot and root fresh weights were not affected by increased media aeration or transplant date (Table 3.5). Final plant height was not affected by increased media aeration (data not presented). Final diameter of control plugs was larger than plugs grown on an increased drainage column (Table 3.4). Neither final height nor final diameter was affected by transplant date (data not presented). Diameter growth rate was greater in plugs grown in the control flat (Fig. 3.12), which helps explain why these plugs had larger final diameters.

Celosia. Final plant height was not affected by treatment or transplant date (Table 3.4). There was no difference in final height between plants grown on an increased drainage column and those grown in the control plug flats, regardless of transplant date. Final diameter was affected by both treatment and transplant date. Plants grown on an increased drainage column and transplanted at the first transplant date had greater final diameters than all other treatments (Table 3.4). Neither height nor diameter growth rate was affected by treatment or transplant date (data not presented).

Petersen et al. (1991) and Dubik et al. (1989) hypothesized that reduced growth in response to root-restriction was caused by low oxygen availability. Growing a plug flat on top of an open flat of media increases the drainage column and can allow for more oxygen availability. We found that growing plugs on a longer drainage column did not result in larger final post-transplant heights for either species. However, final diameter was larger in *Celosia* plants grown on the longer drainage column and transplanted on the first transplant date (Table 3.4). Given that this cultivar of *Celosia* is a (large) bedding plant, an increase in diameter is a positive attribute that enhances marketability, since a rounded growth form is preferable for bedding plants. These results indicate that low oxygen availability could be responsible for post-transplant stunting and lack of branching and that consequently, growing plugs past PPS on a longer drainage column could result in better quality plants. However, it is important to note that the increase in diameter could also be due to plants grown on a longer drainage column having a more consistent source of water. These plugs did not experience the rapid drying out in between watering that plugs grown in the control flat would have experienced. Therefore, it is unclear whether the increased diameter was due to increased oxygen availability or increased water availability. On the other hand, *Catharanthus* plugs were not helped by being grown on a longer drainage column. In fact, final diameter was larger in plugs *not* grown on a longer drainage column (Table 3.4). Pre-transplant data for *Catharanthus* proved, as expected, that plants left in plug flats longer had greater shoot and root dry weights, root areas and root lengths. However, no difference was between treatments was observed (Table 3.5).

Previous studies indicated that drought stress could be responsible for the stunting of root restricted plants (Hameed et al., 1987 and Kharkina et al., 1999). These studies found that even when water is not limited, root restricted plants demonstrate drought stress symptoms. Our studies did not experience this phenomenon. Plugs were kept thoroughly watered before and after transplanting, and we did not experience any drought stress symptoms. Therefore, our study agrees more with the theory shared by several researchers (Krizek et al., 1985; Carmi and Heuer, 1980; Ismail and Noor, 1996; and Peterson et al, 1991) that water stress was not a problem.

Conclusions

The only treatment that has made consistent differences in post-transplant growth was a longer drainage column. This resulted in a larger final diameter in *Celosia* plugs grown on a longer drainage column that were transplanted on time. In all experiments with a direct seeded control (root obstruction, root ball disturbance), plants sown directly into 17 cm (1.66 L) pots were larger (in height and diameter) at the end of the experiments (Tables 3.2 and3.3). Direct seeding may be beneficial for some growers, because it allows for the production of a high quality crop in a relatively short period of time. However, it may not be cost efficient and there is not as much flexibility with the production time as there is with plugs. In some experiments, including GA application time and root ball disturbance, transplant date had a greater effect on final height and/or diameter than any other factor. In these cases, plugs transplanted earlier were larger than those transplanted later by the end of the experiment. These results confirm the importance of transplanting on time.

We are able to conclude that the negative effects of holding plugs for too long after PPS is not caused by a lack of gibberellic acid being supplied to the shoot, the root hitting the container or the inability of the plugs to “spread out” their roots after transplanting. It is possible that low oxygen availability is to blame. Further research needs to be conducted to better determine the role of nutrient deficiency in stunting of root restricted plants, study the role of cytokinins and ABA in plug stunting, experiment with chemical root pruning in plug flats, examine the effect of light quality and quantity on post-transplant performance, and test other species for the effect of increased plug drainage column on post-transplant performance.

Literature Cited

Arnold, M. A. 1996. Mechanical correction and chemical avoidance of circling roots differentially affect post-transplant root regeneration and field establishment of container-grown shumard oak. J. Ameri. Soc. Hort. Sci. 121:258-263.

Ballare', C.L., A.L. Scopel, and R. A. Sanchez. 1995. Plant morphogenesis in canopies, crop growth, and yield. HortScience 30:1172-1181.

Carmi, A. and B. Heuer. 1981. The role of roots in control of bean shoot growth. Ann. Bot. 48:519-527.

Davis, M.H. and S.R. Simmons. 1994. Far-red light reflected from neighboring vegetation promotes shoot elongation and accelerates flowering in spring barley plants. Plant, Cell and Environ. 17:829-836.

Dubik, S.P., D.T. Krizek, and D.P. Smart. 1989. Influence of root zone restriction on morphogenetic responses of spreading euonymus. J. Plant Nutr. 12:1021-1044.

Gouin, F.R. 1984. Updating Landscape Specifications. J. Environ. Hort. 2:98-101

Hameed, M.A., J.B. Reid, and R.N. Rowe. 1987. Root confinement and its effects on the water relations, growth and assimilate partitioning of tomato. Annals Bot. 59:685-692.

Hanson, P.J., R.K. Dixon, and R.E. Dickson. 1987. Effect of container size and shape on the growth of northern red oak seedings. HortScience 22:1293-1295.

Ismail, R.M. and K.M. Noor. 1996. Growth, water relations and physiological processes of starfruit plants under root growth restriction. Scientia Hort. 66:51-58.

Kharkina, T.G., C.O. Ottosen, and E. Rosenqvist. 1999. Effects of root restriction on the growth and physiology of cucumber plants. Physiol. Plant. 105:434-441.

Krizek, D.T., A. Carmi, R.M. Mirecki, F.W. Snyder, and J.A. Bunce. 1985. Comparative effects of soil moisture stress and restricted root zone volume on morphogenetic and physiological responses of soybean. J. Expt. Bot. 36:25-38.

Latimer, J.G. 1991. Container size and shape influence growth and landscape performance of marigold seedlings. HortScience 26: 124-126.

Liu, A. and J.G. Latimer. 1995. Water relations and abscisic acid levels of watermelon as affected by rooting volume restriction. J. Expt. Bot. 46:1011-1015.

NeSmith, D.S. 1993. Summer squash response to root restriction under different light regimes. J. Plant Nutr. 16:765-780.

Peterson, T.A., M.D. Reinsel, and D.T. Krizek. 1991b. Tomato plant response to root restriction: Root respiration and ethylene generation. J. Expt. Bot. 42:1241-1249.

Struve, D.K. 1993. Effect of copper-treated containers on transplant survival and regrowth of four tree species. J. Environ. Hort. 11:196-199.

Styer, R.C. and D.S. Koranski. 1997. Plug and transplant production: a grower's guide. Ball Publishing, Batavia Ill.

van Iersel, M. 1997. Root restriction effects on growth and development of salvia. HortScience 32:1186-1190.

van Iersel, M., P.A. Thomas, R.B. Beverly, J.G. Latimer and H.A. Mills. 1998. Nutrition affects pre- and post-transplant growth of impatiens and petunia plugs. HortScience 33: 1014-1018.

van Iersel, R.B. Beverly, P.A. Thomas, J.G. Latimer, and H.A. Mills. 1999. Nitrogen, phosphorus, and potassium effects on pre- and post-transplant growth of salvia and vinca seedlings. J. Plant Nutr. 22: 1403-1413.

Table 3.1. Effect of gibberellic acid concentration on plant height and diameter of *Catharanthus* and *Celosia* plugs recorded eight weeks after transplanting from the plug flat to 17 cm pots. Means are an average of data from 10 plants.

Transplant date	GA (ppm)	Height (cm)	Diameter (cm)
	Catharanthus		
11 Oct.	0	17.0	10.0 b[z]
	100	18.2	10.8 b
	200	16.2	10.2 b
	400	17.1	11.9 ab
25 Oct.	0	15.4	13.8 a
	100	17.9	10.6 b
	200	17.3	10.5 b
	400	18.4	10.5 b
Significance:			
GA concentration (GA)		NS	NS
Transplant date (D)		NS	NS
GA*D		NS	0.0035
	Celosia		
20 Dec.	0	19.1 a	15.0
	100	18.7 a	13.6
	200	18.9 a	14.4
	400	18.1 a	13.6
3 Jan.	0	18.7 a	14.7
	100	16.8 ab	12.9
	200	14.1 c	13.6
	400	15.5 bc	12.1
Significance:			
GA concentration (GA)		0.0363	NS
Transplant date (D)		0.0003	NS
GA*D		0.1007	NS

[z] Means within columns separated by LSD, $P \leq 0.05$.

Table 3.2. Effect of root obstruction treatments on plant height and diameter of *Catharanthus* plugs recorded eight weeks after transplanting from the plug flat to 17 cm pots. Means are an average data from 10 plants.

Transplant date	Treatment	Height (cm)	Diameter (cm)
--[z]	Direct seeded	27.5 a[y]	51.5 a
28 Jul.	Roots obstructed	22.2 b	31.9 b
	Control	20.6 b	34.7 b
11 Aug.	Roots obstructed	20.6 b	31.8 b
	Control	22.0 b	34.0 b
Significance:			
Treatment (T)		0.0049	0.0001
Transplant date (D)		NS	NS
T*D		NS	NS

[z] n/a

[y] Means within species and columns separated by LSD, $P \leq 0.05$.

Table 3.3. Effect of root ball disturbance on plant height and diameter of *Catharanthus* and *Celosia* plugs recorded eight weeks after transplanting from the plug flat to 17 cm pots. Means are an average data from 10 plants.

Transplant date	Treatment	Height (cm)	Diameter (cm)
	Catharanthus		
--[z]	Direct seeded	27.5 a[y]	51.5 a
28 Jul.	Rootball disturbed	21.5 b	32.1 b
	Control	20.6 b	34.7 b
11 Aug.	Rootball disturbed	19.2 b	31.9 b
	Control	22.0 b	34.0 b
Significance:			
Treatment (T)		0.0018	0.0001
Transplant Date (D)		NS	NS
D*T		NS	NS
	Celosia		
--[z]	Direct seeded	40.4 a[y]	27.23 a
6 Dec.	Rootball disturbed	21.5 b	12.2 cd
	Control	21.6 b	15.3 b
20 Dec.	Rootball disturbed	16.3 cd	13.5 bcd
	Control	18.1 c	14.5 bc
Jan. 3	Rootball disturbed	17.0 cd	12.0 cd
	Control	15.2 d	11.3 d
Signifnicance:			
Treatment (T)		0.0001	0.0001
Transplant date (D)		0.0001	0.0470
T*D		NS	NS

[z] n/a

[y]Means within columns separated by LSD, $P \leq 0.05$.

Table 3.4. Effect of increased media aeration on plant height and diameter of *Catharanthus* and *Celosia* plugs recorded eight weeks after transplanting from the plug flat to 17 cm pots. Means are an average data from 10 plants.

Transplant date	Treatment	Height (cm)	Diameter (cm)
	Catharanthus		
8 Sept.	Media aeration	17.4	14.4b[z]
	Control	17.7	18.9a
22 Sept.	Media aeration	14.5	14.0b
	Control	17.5	18.7a
Significance:			
Treatment (T)		NS	0.0001
Transplant date (D)		NS	NS
T*D		NS	NS
	Celosia		
27 Dec.	Media aeration	20.2	16.1 a[z]
	Control	18.6	12.1 b
10 Jan.	Media aeration	20.1	12.8 b
	Control	19.7	10.8 b
Significance:			
Treatment (T)		NS	0.0024
Transplant date (D)		NS	NS
T*D		NS	NS

[z] Means within columns separated by LSD, $P \leq 0.05$.

Table 3.5. Effect of media aeration on plug quality rating, shoot and root fresh weight and dry weight, root area, and root length of *Catharanthus* plugs recorded two days before transplanting from the plug flat to 17 cm pots. Means are an average data from 10 plants.

Transplant date	Treatment	Plug quality	Fresh weight (mg) Shoot	Fresh weight (mg) Root	Dry weight (mg) Shoot	Dry weight (mg) Root	Root area (cm^2)	Root length (cm)
8 Sept.	Media aeration	3.9	236.0	43.7	27.9 b[z]	2.9 ab	1.2 b	16.4 b
	Control	3.5	228.0	33.3	28.4 b	1.9 b	1.0 b	14.5 b
22 Sept.	Media aeration	4.1	330.0	54.4	49.9 a	3.8 ab	4.8 a	40.8 a
	Control	3.7	304.8	58.5	43.8 ab	4.3 a	4.8 a	42.1 a
Significance:								
Treatment (T)		NS	NS	NS	NS	NS	NS	NS
Transplant date (D)		NS	NS	NS	0.0054	0.0463	0.0001	0.0001
T*D		NS	NS	NS	NS	NS	NS	NS

[z] Means within columns separated by LSD, $P \leq 0.05$.

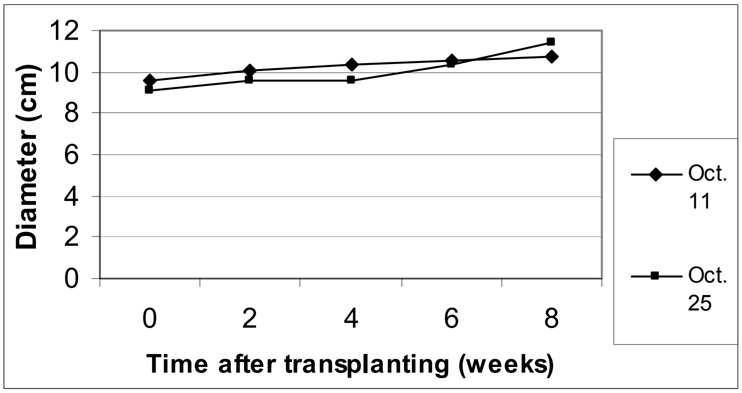


Fig. 3.1. Influence of transplant date on diameter (cm) of *Catharanthus* plugs treated with gibberelic acid at varying concentrations. Slopes are significantly different at P=0.0475.

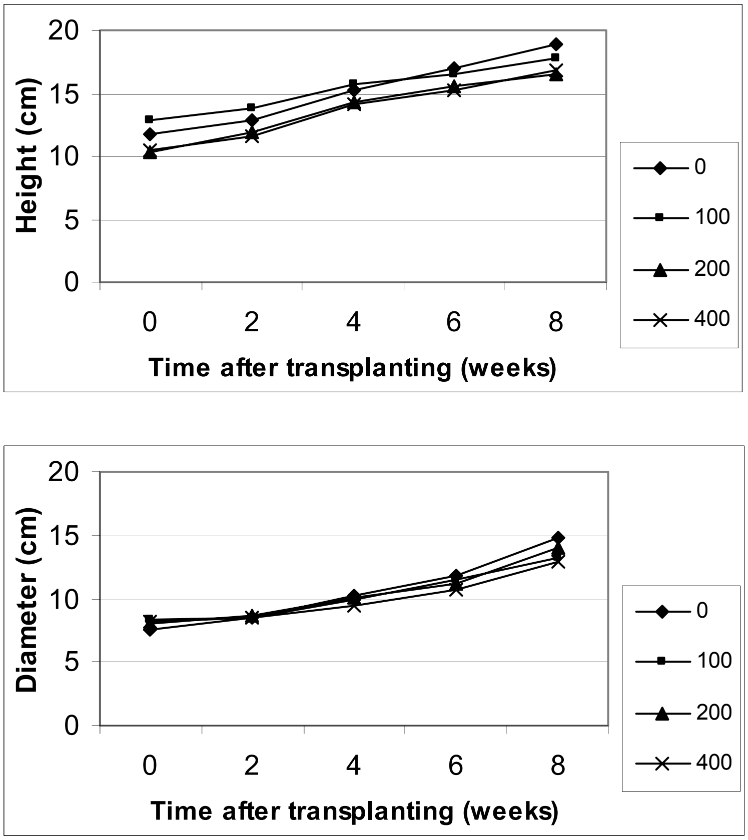


Fig. 3.2. Influence of 0, 100, 200 or 400 ppm gibberelic acid on height (cm) and diameter (cm) of *Celosia* plugs. Height slopes of 0 and 100 ppm are significantly different at P=0.0289. Diameter slopes of 0 and 400 ppm are significantly different at P=0.0227. All other slope contrasts are not statistically significant.

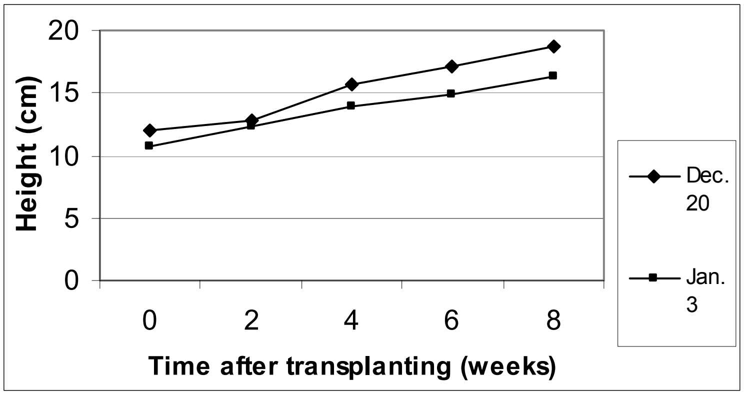
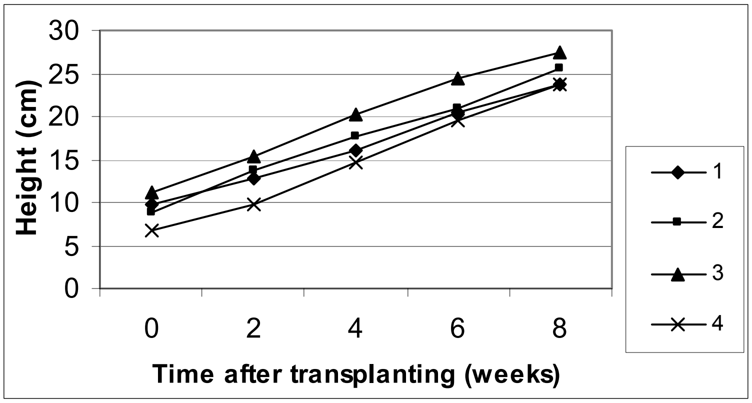


Fig. 3.3. Influence of transplant date on height (cm) of *Celosia* plugs treated with gibberellic acid at varying concentrations. Slopes are significantly different at P=0.0180.



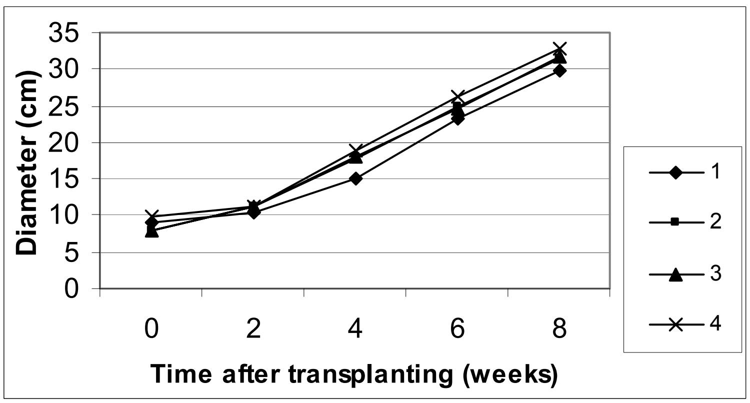


Fig. 3.4. Influence of gibberellic acid (GA) application time on height (cm) and diameter (cm) of *Catharanthus* plugs. 1= GA applied two weeks before transplanting. 2= GA applied one week before transplanting. 3= GA applied two weeks before transplanting and again one week before transplanting. 4= Control – no GA applied. Height slopes of 1 and 4 are significantly different at P=0.0190. Diameter slopes of 1 and 4 are significantly different at P=0.0484. All other slope contrasts are not statistically significant.

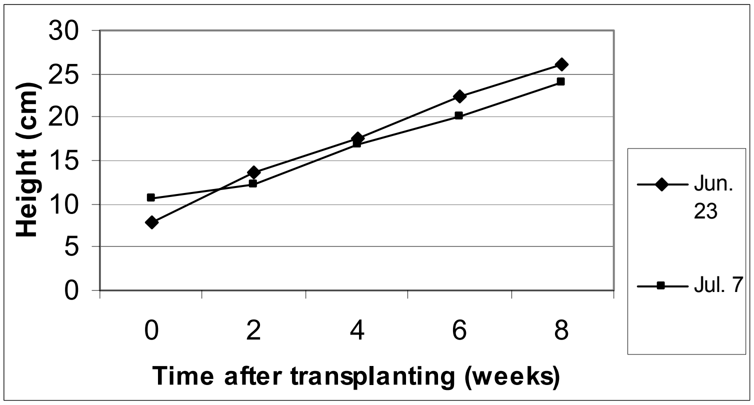


Fig. 3.5 Influence of transplant date on height (cm) of *Catharanthus* plugs treated with gibberellic acid (400 ppm) at various application times. Slopes are significantly different at P= 0.0003.

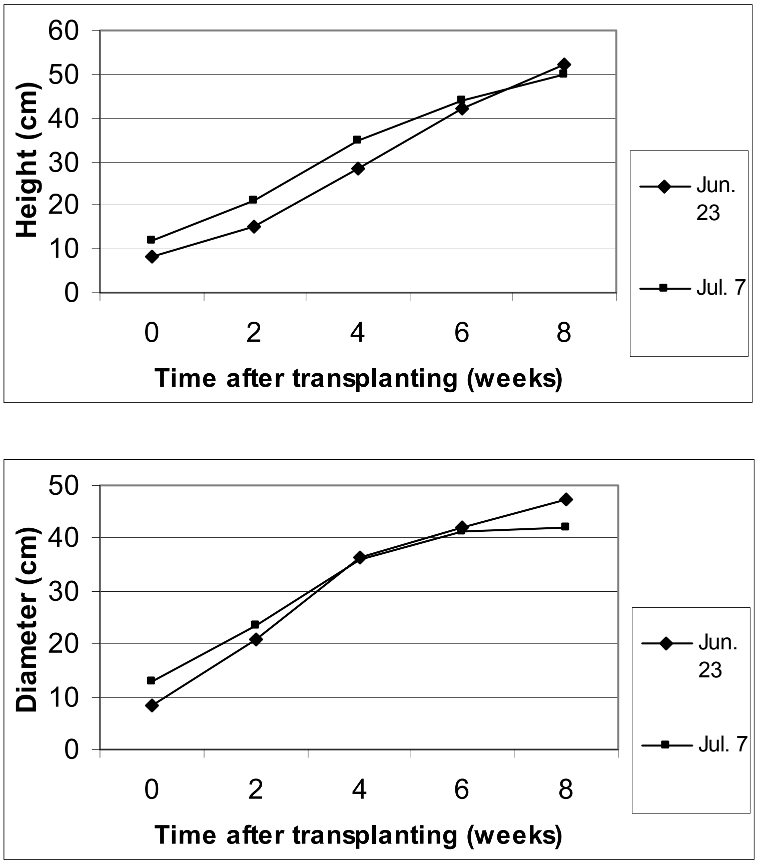
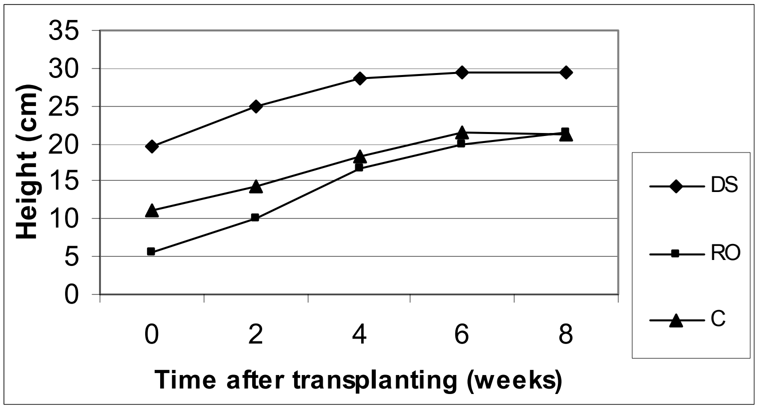


Fig. 3.6. Influence of transplant date on height (cm) and diameter (cm) of *Celosia* plugs treated with giberellic acid (400 ppm) at various application times. Height slopes are significantly different at $P=0.0021$ and diameter slopes are significantly different at $P\leq0.0001$.



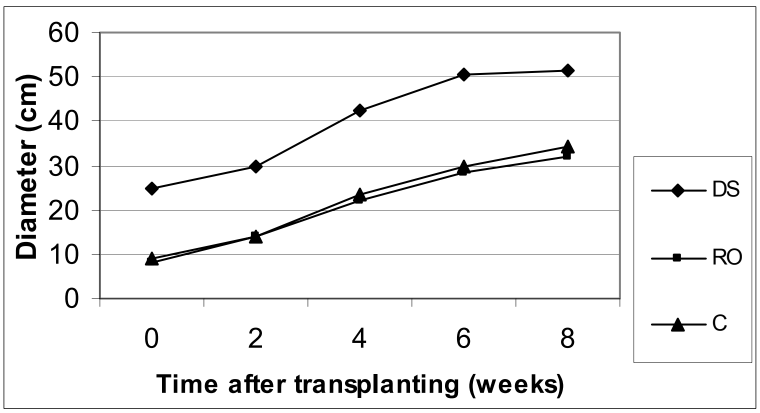


Fig. 3.7. Influence of root obstruction treatment on height (cm) and diameter (cm) of *Catharanthus* plugs. DS = directed seeded plants. C = Control plugs. RO = Root obstructed plugs. All other slope contrasts are not significantly different. Height slopes of DS and RO are significantly different at $P \leq 0.0001$. Height slopes of RO vs. ROC are significantly different at $P=0.0003$. Diameter slopes of DS and RO are significantly different at $P=0.0041$.

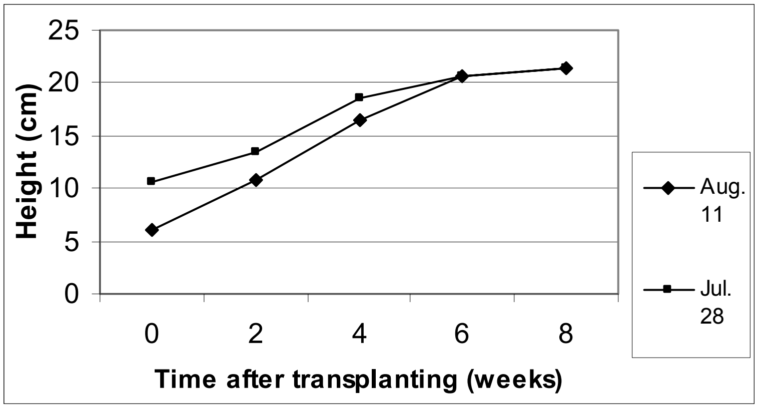


Fig. 3.8. Influence of transplant date on height (cm) of *Catharanthus* plugs subjected to root obstruction and control treatments. Slopes are significantly different at P= 0.0023.

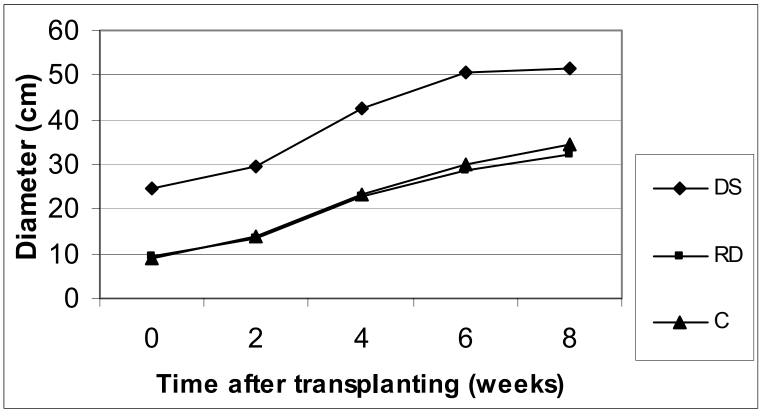


Fig. 3.9. Influence of root ball disturbance treatments on diameter (cm) of *Catharanthus* plugs. DS = direct seeded plants. RD= plugs with root balls disturbed. C= control plugs (no root ball disturbance). Slopes of DS and RD are significantly different at P=0.0009.

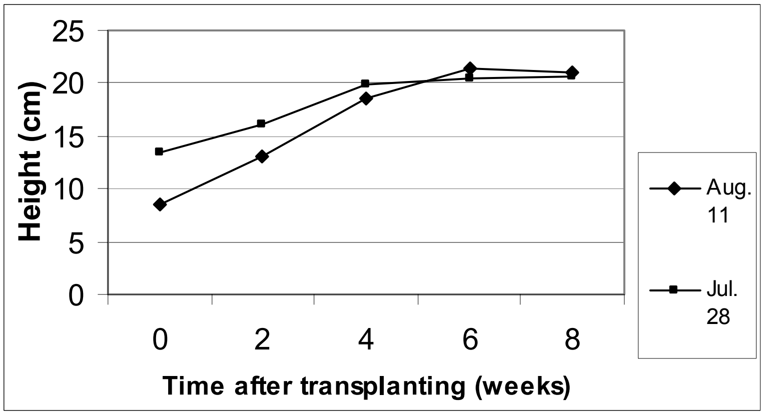
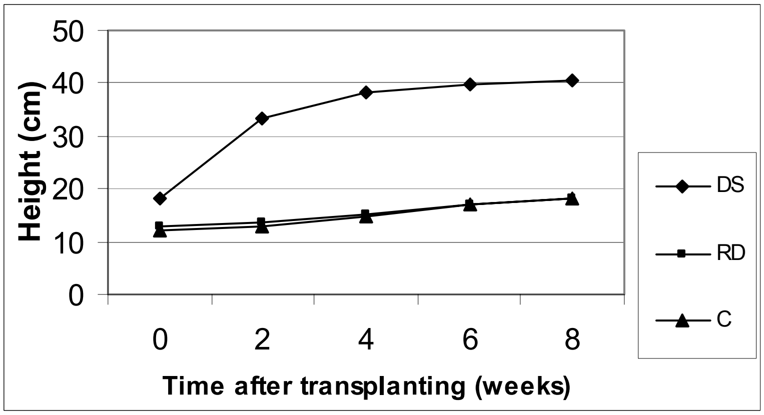


Fig. 3.10. Influence of transplant date on height (cm) of *Catharanthus* plugs subjected to root disturbance and control treatments. Slopes are significantly different at P≤0.0001.



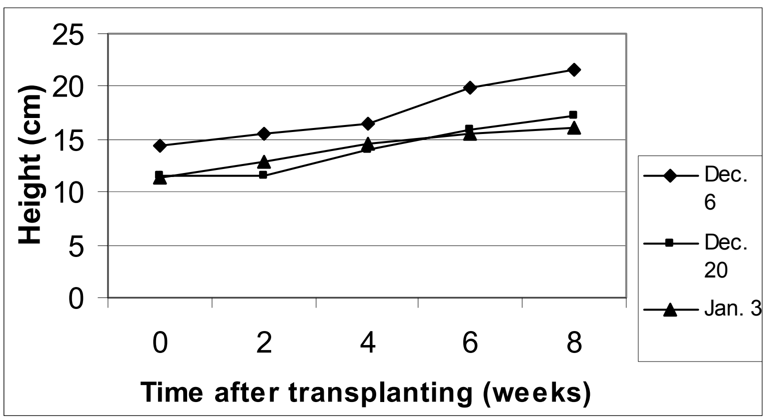


Fig. 3.11. Influence of root ball disturbance treatments and transplant date on height (cm) of *Celosia* plugs. DS = direct seeded plants. RD= plugs with root balls disturbed. C= control plugs (no root ball disturbance). Slopes of DS and RD are significantly different at $P \leq 0.0001$. Slopes of DS and C are also significantly different at $P \leq 0.0001$. Slopes of transplant dates are significantly different at $P=0.0215$.

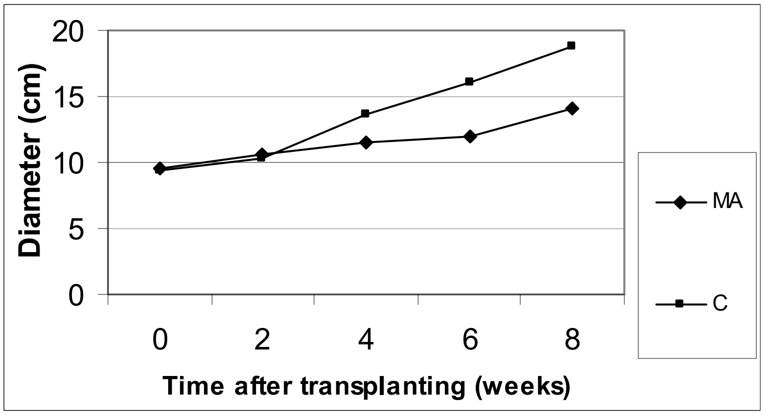


Fig. 3.12. Influence of a longer drainage column on diameter (cm) of *Catharanthus* plugs. MA=Media aeration (plugs grown on a longer drainage column). C=Control. Slopes are significantly different at $P \leq 0.0001$.

CHAPTER IV

SUMMARY

Some species are sensitive to the negative effects of being grown in plug flats, including *Callistephus, Celosia, Consolida, Dianthus,* and *Tagetes* and should be transplanted at PPS. While it is best to transplant plugs on time, several species are not as sensitive to the amount of time held in plug flats after PPS. These species include: *Antirrhinum, Brassica, Begonia, Eustoma, Gazania, Impatiens, Lycopersicon, Matthiola* 'Christmas Ruby' and 'Harmony Cherry Blossom', and *Viola*. Hundreds of other species are grown by the floriculture industry and should also be tested. Research also needs to determine the causes of the stunting caused by plug flat holding and methods of overcoming this problem.

The only treatment that has made a consistent difference in post-transplant growth was a longer drainage column. This resulted in a larger diameter in *Celosia* plugs grown on a longer drainage column that were transplanted on time. In all experiments with a direct seeded control (root obstruction, root ball disturbance), plants sown directly into 17 cm (1.66 L) pots were larger (in height and diameter) at the end of the experiments (Tables 3.2 and 3.3). Direct seeding may be beneficial for some growers, because it allows for the production of a high quality crop in a relatively short period of time. However, it may not be cost efficient and there is not as much flexibility with the production time as there is with plugs. In the GA application time and root ball disturbance experiments, transplant date had a greater effect on final height and/or diameter than any other factor. In these cases, plugs transplanted earlier were larger than those transplanted later by the end of the experiment. These results confirm the importance of transplanting on time.

We are able to conclude that the negative effects of holding plugs for too long after PPS are not caused by a lack of gibberellic acid being supplied to the shoot, the root hitting the container or the inability of the plugs to “spread out” their roots after transplanting. It is possible that low oxygen availability is to cause. Further research needs to be conducted to better determine the role of nutrient deficiency in stunting of root restricted plants, study the role of cytokinins and ABA in plug stunting, experiment with chemical root pruning in plug flats, examine the effect of light quality and quantity on post-transplant performance, and test other species for the effect of increased plug drainage column on post-transplant performance.