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Current Status of Growth Regulator Usage in Flower Bulb Forcing in North America

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ABSTRACT

North American greenhouse companies are mainly focused on potted crops, and due to lower geographical concentration, individual greenhouse firms, tend to have a very diversified product offering. As such, individual crops are often grown under less than optimum conditions. Plant growth regulators offer a set of tools that allow growers to better tailor bulb crops to containers, and the more liberal market and regulatory environment in North America continues to allow a high degree of specialization of PGR use. It is hoped the specific PGR and crop information presented herein and available online will stimulate additional research and interest in these products and crop uses worldwide.

Keywords: Ethephon, flurprimidol, paclobutrazol, uniconazole, *Hyacinthus*, *Lilium*, *Narcissus*, *Tulipa*

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INTRODUCTION

Geophytes (flower bulbs) are an important part of global floriculture (Benschop *et al*. 2010). While the Netherlands is the global leader in both bulb and bulb flower production, many bulbs are exported worldwide for greenhouse forcing, landscape and garden use. In total, flower bulbs comprise slightly less than 10% of the total pot plant market in the United States, but since their production tends to be concentrated at larger growers, bulbs represent a significant proportion of the annual production of many North American greenhouses (**Table 1**). Their quick greenhouse time, close spacing during production and potentially low temperature requirements for forcing all contribute to relatively low overhead and production costs. Also, because spring flowering geophytes (e.g., tulips, daffodils, hyacinth, crocus, etc.), require little if any fertilization during production and have limited pest problems, they have the potential to become known as a "green" product that could be even more attractive to consumers.

Unlike most of the world's floriculture industry where cut flowers predominate, in North America, the majority of bulb flowers (indeed, the majority of floricultural crops) are grown in pots or other containers. As such, because of the aesthetic ratio (Sachs *et al*. 1976) many crops and cultivars are too tall when grown in 10 cm or 15 cm pots. Therefore, a variety of height control technologies are needed for pot bulb production. Techniques such as temperature management (e.g. negative DIF [DIF is the difference of night temperature minus day temperature], where plants are grown

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Invited Mini-Review

Table 1 Dollar value of container-grown floral crops in the United States from 2006-2011. Source: USDA-NASS (2011).

Crop	2006	2007	2008	2009	2010	2011	2011 (%)
African violets	8.0	6.5	4.5	3.6	3.6	3.4	0.5%
Azaleas	34.9	28.7	35.9	31	26.2	21.0	3.3%
Chrysanthemums	40.8	40.0	35.2	24.8	24.0	21.7	3.4%
Easter lilies	26.1	26.9	24.7	27.4	26.8	22.4	3.5%
Orchids	120.5	126.0	137.4	161.2	170.8	191.3	29.9%
Poinsettias	171.0	161.0	153.7	148.6	146.1	139.2	21.7%
Roses	21.4	23.0	25.8	23.1	26.9	23.6	3.7%
Spring bulbs	47.4	46.5	54.6	46.7	59.8	53.6	8.4%
Other	151.2	182.1	225.8	176.6	184.3	163.9	25.6%
TOTAL	$621.3	$640.7	$697.6	$643.0	$668.5	$640.1	100%

warmer at night than the day, Erwin *et al.* 1989), light spectrum modification (e.g., covering plants with blackout cloth before the end-of-day burst of far-red light, Blom *et al.* 1995), overhead irrigation with cold water to "thermally shock" the apical expansion region (Blom *et al.* 2004) can all be useful for height control. Wise cultivar choices and other cultural practices are also important for height management.

Ultimately, however, the most common method of height management for the industry is the application of plant growth regulators (PGRs) whose mode of action is to inhibit gibberellin biosynthesis or, less commonly, by releasing ethylene. Restriction of height is by far the most important use of PGRs in the production of flower bulb crops.

Postharvest or postproduction longevity is another area of concern in the industry. Bulbous plants and flowers usually have relatively limited flower life, and easily adopted methodologies to improve flower life are welcomed by the industry. In recent years, specific gibberellin and/or cytokinin treatments have been developed and are being used in the industry.

In this review, I will review the current status of growth regulator usage in North American flower bulb forcing, especially in the context of pot plants. A comparison of the North American forcing system to the traditional Dutch system will be made to explain why PGR use is so widespread and advanced in North America. It is hoped this information will stimulate additional flower bulb research in potted bulbs in other areas of the world and, overall, to improve the quality and utility of these products.

UNIQUE CHARACTERISTICS OF THE NORTH AMERICAN FLORICULTURE INDUSTRY

A long recognized strength of concentrated production regions, like the Netherlands, is that individual growers focus on a single species (chrysanthemum, rose, gerbera), and usually are specialized in just a few cultivars of the crop (Ball 1985). Such specialization can exist only when there is concentrated production so the entire market can be supplied with all the needed product. In principle, this specialization results in technologies and procedures that are optimized for plant quality, use of capital or economic return. In many cases, production is on a fairly consistent level throughout the year, although growers of spring bedding plants and perennials obviously have a main busy season.

In the Dutch floriculture industry, there are also companies specialized in bulb growing, bulb preparation (delivery of the specific temperature treatments or sequences that are required per product and use), materials handling (planting substrate, fertilizers, etc.), forcing (with highly specialized and specific systems, for example hydroponic forcing), selling (e.g., through the Dutch auction system) and delivery logistics. The fact The Netherlands is a very small country (by surface area) forces this concentration to some extent, but its small size is a real advantage in terms of transport costs, time, etc. Such efficiencies and concentration are also apparent in Denmark and certain other greenhouse production locations in the world. The overriding characteristic is simplification, specialization and specific expertise residing in the companies responsible for each part of the business chain.

By contrast, the industry in North America is nearly the opposite. It is a fragmented industry and widely dispersed geographically (although there are major greenhouse production states or regions, e.g., California, Florida or Michigan and Ontario, Canada). The North American industry is largely holiday or date driven. For example, a greenhouse grower might be responsible for delivery of Christmas poinsettias to hundreds of store locations for a single large retailer along the eastern US coast, Midwest, or across the southeastern states. In other words, an even, constant volume of production over a relatively long time (as in the Dutch flower industry) is rare in the North American greenhouse industry, especially with potted plants.

Further, the typical greenhouse firm in North America grows tens, if not hundreds of species or cultivars in the main spring season. If one considers a "crop" as a cultivar or variety destined for sale at a certain date, a large greenhouse business can easily contain thousands of specifically

Table 2 Typical container sizes used for pot plant production of bulbous plants in North America.

Crop	Container size(s), cm diameter
Allium karataviense, etc.	15 [z]
Allium christophii, *giganteum*, 'Globemaster'	15, 20[z]
Allium moly	10 [z]
Alstroemeria	20, >20 [z]
Hippeastrum (Amaryllis)	15, 20
Anemone coronaria	15
Caladium	15, 20, >20 [y]
Crocus	10
Dahlia	15, 20, >20 [y]
Eucomis	15 [y]
Freesia	10, 15
Gladiolus	15, 20 [z]
Hyacinthus	10, 15
Iris reticulata, *I. danfordiae*	10
Leucojum aestivum	10, 15
Liatris spicata	20 [z]
Lilium longiflorum	15, 20
Lilium hybrids (Asiatic, LA, Oriental, OT)	12.5, 15, 20, >20 [y]
Muscari	10
Narcissus (large)	15, 20
Narcissus tazetta (paperwhite narcissus)	10, 15, 20
Narcissus, 'Tete-a-Tete'	10
Ornithogalum dubium	10, 12.5
Oxalis regnellii, *O. triangularis*, etc.	10, 15 [y]
Ranunculus asiaticus	15
Scilla	10
Tulipa	10, 15, 20, >20
Zantedeschia	10, 15, 20[y]

[z] Indicates plants mainly grown for outdoor use or planting in the ground, and not as potted plants *per se*.
[y] Indicates plants commonly grown as indoor pot plants and also for outdoor patio or balcony decoration, or for in-ground planting.

grown "crops". Within this complexity, flower bulb forcing is usually not the major part of the entire spring crop mix in many greenhouses.

As mentioned above, bulb forcing in North America is dominated by pot plant production. Bulbous plants are grown in a range of container sizes (**Table 2**) so the optimal plant size within a species (or even cultivar) varies by pot size.

MAIN BULB FORCING SYSTEMS

De Hertogh and Le Nard (1993) and De Hertogh (1996) and have reviewed the basic bulb forcing systems used in North America. Very briefly, spring-flowering crops that are normally planted in the fall are called "rooting room bulbs" since they undergo a lengthy (10-20 week) period of low temperature (1-9°C), with much of the cold occurring after planting. They are removed from the cooler, placed in a greenhouse, and normally develop and flower rapidly (within 1-4 weeks in most cases).

Non-rooting room crops include many species that are "summer flowering" species. While many of these crops require a cold treatment to flower, and, if needed, must undergo a potentially lengthy cold storage before planting (e.g., lilies are cooled a minimum of 6 weeks at 4-5°C, to as long as a year, frozen, at -1-2°C), they typically have a much longer growing period before anthesis, and have an overall higher light requirement than spring flowering bulbs such as tulip, hyacinth or narcissus.

There are a number of deviations and modifications of the above two systems, but most pot plant or cut flower bulb forcing falls within one of these categories.

FACTORS AFFECTING PLANT HEIGHT IN BULBOUS CROPS

Numerous factors affect height of plants, some of the most important for greenhouse forcers of flower bulb crops are outlined below.

Cultivar

Within a defined environment, the genetic makeup of a cultivar ultimately determines final plant height and overall performance. Within the major bulbous genera (*Tulipa*, *Zantedeschia*, *Gladiolus*, *Iris* and *Lilium*) the major sustained breeding efforts have been to develop cultivars for use as cut flowers (van Tuyl and Arens 2011). To the present time (with some notable exceptions) specific breeding programs to develop cultivars for pot plant use have been neglected. Therefore, for effective performance in pots, a reduction in the potential height is needed for most cultivars of most geophytic genera.

On the other hand, an increasing number of genetically dwarf, compact-growing cultivars of the main genera, especially tulip, lily and *Zantedeschia* are being released in the bulb trade. Ultimately, one can expect that breeding can eliminate the need for many of the cultural or chemical means of height control. Within North America, however, the range of cultivars needed for the entire forcing season, in the color range and flower form needed, without PGRs, simply does not yet exist.

Another aspect of the adoption of new germplasm is wide availability of the material, knowledge of the material on the part of the grower, and cost. Simply due to newness in the market, or to more sophisticated production management (i.e., tighter controls on the germplasm and production acreage), it is to be expected that new dwarf varieties that save direct chemical and indirect management costs will be more expensive than older, common varieties. In the opinion of the author, individual bulb forcers will make a determination as to the economic feasibility of any new varieties. Therefore, while there is an increasing emphasis on cultivars adapted to pot culture without the need for PGR's, until growers become familiar with these cultivars (or, their prices fall or availability becomes similar to current cultivars) PGR use will continue.

Length of cold

Tulips, daffodils, and hyacinths all share a common characteristic: the longer the length of cooling (and rooting) before forcing, the taller the plant ultimately will be (Rees and Turquand 1969). For example, **Fig. 1** shows 15 cm pots of tulip cultivar 'All Seasons' given 14 or 23 weeks of cold (initially 9°C, then decreasing to 1°C as rooting and shoot growth progressed) and forced in the greenhouse. The extra elongation from the longer cold period is clearly seen. Therefore, simply giving the correct cold period by not exposing plants to excessive lengths of cold can achieve a significant degree of height control.

The issue in North America is that most growers want to plant their entire bulb crop at one time (October to early November) to keep labor available for packaging and shipping the Christmas poinsettia (or other) crops from mid-November through December. While efficient at the start, this method causes excessive cold duration and usually leads to excessive height and lost quality for the last crops of the year (Easter and Mother's Day).

Rooting and cooling temperature

The temperature used in the rooting room has a profound effect on height, but many variations occur across crops. For example, hyacinths grown for cut flower use are cooled at 9°C, a temperature that allows rooting and significant stem elongation before the crop is moved into light for forcing and "greening up". Cooling them at lower temperatures restricts stem growth in the cooler and therefore leads to shorter plants upon flowering. In tulip, colder "cooling" temperatures lead to taller and faster flowering plants (Rees and Turquand 1969).

Forcing temperature

Effects of greenhouse forcing temperature vary a great deal by crop, growth stage, light level and other environmental factors. For example, tulips were taller when grown at 21/18°C (day/night) compared with 3°C higher temperatures (Nelson and Niedziela 1998), but *Lilium longiflorum* is usually taller when grown under warmer conditions (Miller 1992).

Negative DIF

Many plants respond to the difference in day and night temperatures, and warmer nights than days (a negative DIF, where DIF = night temperature - day temperature) usually reduces stem elongation (Erwin *et al*. 1989). Negative DIF, or zero DIF (equal night and day greenhouse temperature) produces plants that are shorter than plants with warmer days than nights (when all are grown at the same 24-h average temperature). Temperature manipulation is widely used to control height of *L. longiflorum*, and somewhat less on the various hybrid lilies. *Dahlia* is another major bulbous crop that responds to DIF (Brøndum and Heins 1993). Most "spring bulb" crops are apparently not highly responsive to negative DIF for height control (Erwin *et al*. 1989).

Other cultural and environmental techniques

Blom *et al*. (1995) found that excluding the end-of-day burst of far-red light (via blackcloth) resulted in significantly less stem elongation in *L. longiflorum* and Blom *et al*. (2004) demonstrated that overhead irrigation with cold water results in substantial height reduction in Easter lily. This effect is due to cold temperatures on the shoot tip and it not an effect of temperature on the growing media.

In North America, most flower bulb crops are grown without CO_2 supplementation. The main rooting room crops







Fig. 1 Effect of cold-weeks and PGR treatment drenches on appearance of 15 cm tulip 'All Seasons'. Cold duration after planting was 12 weeks (top) or 21 weeks (bottom). In each panel, L to R: Control, 1 or 2 mg paclobutrazol applied as a soil drench 1-3 days after placing in the greenhouse. For all figures, plants were grown at 17°C constant temperature and full sun within a glass greenhouse in central New York state (Cornell University).

Fig. 2 Narcissus 'Tete a Tete'. While a miniature plant for growers, it shows robust growth in the postharvest chain. Left: plant in a 10 cm pot at the stage of the first flower opening. Right: similar plant 10 days older, after being in a typical interior environment at 20°C.

Fig. 3 Effect of PGR concentration on tulip 'Passionale' when applied as a 10 minute pre-plant bulb soak. L to R: Control (water soak), 50, 100, 200 or 400 mg/l paclobutrazol, and 5, 10, 20 and 40 mg/l uniconazole. After soaking, bulbs were planted then cooled for 16 weeks prior to forcing.

Fig. 4 Long-term effectiveness of growth regulator dip treatment on tulip. 'Purple Flag' tulips were dipped 50 mg/l paclobutrazol for 10 min, then held dry and ventilated for various durations at 17°C before planting and cooling. L to R: Seven tall plants (controls, dipped into water 6, 5, 4, 3, 2, 1 or 0 weeks. Seven short plants: dipped into paclobutrazole 6, 5, 4, 3, 2, 1, 0 weeks before planting and cooling.

Fig. 5 Importance of cultivar selection. Hyacinth 'Blue Jacket' (left) and 'Delft Blue' (right). Both in 10 cm pots and cooled for 15 weeks.

Fig. 6 Effect of pre-plant flurprimidol bulb dips on hyacinth 'Miss Saigon' in 10 cm pots, cooled for 16 weeks. Bulbs were dipped for (left to right): 0 (water control), 5, 10 or 30 minutes into 30 mg/l flurprimidol, or a 30 mg/l flurprimidol bulb spray.

Fig. 7 Effect of pre-plant flurprimidol bulb dips on narcissus 'Ice Follies' and postharvest growth control. Bulbs were dipped into 25 mg/l flurprimidol for L to R: 0, 5, 10, or 30 min. Top: at start of flowering, bottom, near the end of flowering. Same plants in each photo.

(tulip, hyacinth, narcissus, crocus) are grown with very simple fertilization schemes, mainly calcium nitrate (especially for tulips to prevent stem topple). Irrigation is critical for normal growth, and a lack of water can easily cause flower abortion (drying up) during forcing. While these and other cultural techniques are essential for proper growth, it is doubtful that manipulation of them *per se* is likely to be an effective height control technique.

Postharvest or postproduction elongation

In many cases, the real issue for growth regulation for bulb crops is not height control during production *per se*, since most spring bulbs (tulip, hyacinth, narcissus, crocus, muscari, etc.) are quite compact when sold at the proper market stage. Instead, control of unwanted growth in the postharvest chain (retail and end-user phases) is of paramount importance. This is clearly seen in **Fig. 2**, showing the miniature 'Tête-à-Tête' daffodil as it appears during marketing, and after 7 days in a typical interior (consumer) environment at 20°C. Similar postharvest growth is seen in many hyacinth cultivars. Thus, spring bulb growth regulation is often a case of PGR application in the greenhouse for growth control in the low light and rather warm interior consumer environment.

PLANT GROWTH REGULATORS (PGRs)

In the last 10 years, a number of growth regulators have reached the end of their patent life and as a result the number of products had increased, and prices have fallen as generic products have entered the market. The regulatory environment and market acceptance of PGRs is relatively healthy, especially in North America leading to many options for growers in terms of the breadth and cost of available materials. The situation is significantly more favorable than in Europe, where fewer growth regulators are registered for use. The main active ingredients used in North American floriculture and uses in bulbous crops are given in **Table 3**.

Within the PGR category, the growth retardants have two main modes of activity. The anti-GA materials (ancymidol, chlormequat chloride, daminozide, fluprimidol, paclobutrazol, uniconazole) act by inhibiting endogenous gibberellin synthesis in the plant (Rademacher 2000). Decreased levels of gibberellin are expressed as shorter plants, nearly always with the same number of nodes. Ethephon application results in ethylene release within plant tissues, (or in the root zone) leading to shorter, thicker cells and, ultimately, shorter stems.

PGR application techniques

Three major methods are used to apply PGRs to bulbous crops: pre-plant bulb (storage organ) dip or soak, foliar spray or substrate drench. They are outlined below.

1. Pre-plant bulb dip or soak

Bulbs can be dipped or soaked into solutions of the PGR. Typical durations of immersion are 1 to 5 min, although longer or shorter durations may be adopted as a result of individual grower experimentation. Generally, the material is allowed to drain away, and bulbs are planted within a few hours of dipping. The PGRs commonly used as bulb dips or soaks are highly xylem mobile (flurprimidol, paclobutrazol and uniconazole). Depending on the crop (and cultivar) and PGR, pre-plant dips can be remarkably effective (**Fig. 3**).

Benefits of pre-plant bulb soaks include ease of application, allowing many bulbs to be treated in a small area, cost effectiveness and uniformity of response. Disadvantages include the need to apply the PGR before the forcing season, and once treated, the material cannot be removed. At the time of writing, bulb dips are being increasingly used for hyacinth and narcissus, but somewhat less so for tulip.

Research (Ranwala *et al*. 2005; Krug *et al*. 2006b) has shown the most commonly used PGRs solutions maintain effectiveness even after many bulbs have been dipped so that under most practical situations, the dip solution can be used over and over. Unpublished research from the author showed that flurprimidol solutions kept in darkness maintained activity for at least 7 weeks.

Krug *et al.* (2006b) showed hyacinths can be dipped at least 7 days before planting without a difference in effectiveness. It is likely this time frame is even longer for many bulbs, as unpublished data from Miller shows tulips can be dipped at least 6 weeks before planting, with no difference in activity, suggesting the potential to market "pre-growth-regulated" bulbs in the future (**Fig. 4**).

2. Foliar spray

Since mature leaves and the stem are the main spray droplet contact surface, the earliest chemicals used as foliar sprays are generally phloem-mobile (daminozide, chlormequat-chloride), and tended to be active only at relatively high concentrations (generally in the 500-2,500 mg l^{-1} range). These materials are traditionally applied at a relatively high volume, hence recommendations to "spray to runoff". Since the materials were mainly phloem mobile, the excess material entering the rootzone from high volume applications had little if any effect on growth.

The advent of the xylem mobile triazoles paclobutrazol and uniconazole, which are generally very effective as foliar sprays, lead to the realization that substantial PGR activity can also result from root uptake from material that contacts the media surface (Barrett and Bartuska 1982). Barret *et al*. (1994) further refined our understanding of these effects by showing that volume of spray per crop area has a major influence on triazole activity. Higher spray volumes per area (with a constant concentration) gave much greater effect than lesser volumes. This was shown to be due to increased stem coverage and as a result of PGR active ingredient running down stems and into soil, where it was available for root uptake. Essentially, higher spray volumes give a "drench" effect (see below).

The time of application of foliar sprays is obviously after a significant degree of leaf surface has formed, but before significant stem elongation has occurred. It is axiomatic, but important to realize that PGRs act by *reducing future growth* and do not "shrink" plants.

3. Media drench

Assuming there is an actively functioning root system, application of PGRs to the rootzone is often the most effective way to control plant height, and often offers a longer-term suppression of stem elongation. Thus, for most spring bulbs, the primary PGR application is by "soil" (media) drench. This is especially true for tulip, and to date the major products used have been ancymidol (A-Rest), paclobutrazol (Bonzi), and most recently flurprimidol (Topflor).

The optimum drench volume is that which completely saturate the media with PGR solution, and allows less than *ca*. 10% of the applied volume to leach. This is especially true for bulb crops where the majority of the roots are usually located in the bottom third to half of the rootzone. Typically, drenches are applied in 60 or 120 ml for 10 cm and 15 cm pots, respectively, and common recipes are given **Table 4**. Plants should be watered 24 or fewer hours before applying the drench to assure even root zone moisture content, and uniform distribution of the PGR drench into the pot. Drenching into an overly dry root zone may lead to uneven growth from channeling, or at the very least, less PGR effect from the material not penetrating to the bottom third of the pot where the roots are.

The timing of drench applications can be significantly earlier than sprays, the major requirement being the presence of roots to absorb the chemical.

The rate ranges, products and application methods are given in **Table 3** for the major bulb crops.

STATUS OF PGR USE FOR HEIGHT CONTROL ON BULB CROPS IN NORTH AMERICA

Rooting room crops

1. Tulip

In the United States and Canada, rootzone drenching is the major method for PGR application on potted tulips. Sprays are not used, and while pre-plant dipping is being trialed on a limited basis by individual growers, dips have not entered into widespread use. The typical treatment is to apply paclobutrazol, ancymidol or flurprimidol drenches within a few

Table 3 This table is intended to give examples of sources for PGR use practices as they currently exist in North America. It is not meant to be an exhaustive literature summary of PGR activity in all geophytic crops.

Active ingredient	Chemical name	Trade name(s)	Formulation	Crop	Method of application	Rate	Reference
Anti-gibberellin growth retardants for height control							
Ancymidol	α-cyclopropyl-α-(*p*-methoxyphenyl)-5-pyrimidinemethanol	A-Rest (also Quel, EL-531), Abide	Liquid, 0.0264%	*Dahlia*	Drench	0.5-2 mg/pot	De Hertogh 1996
				Lilium longiflorum	Foliar spray	33 mg/L	Miller 1992
				Lilium longiflorum	Drench	0.25-0.5 mg/pot	Miller 1992
				Oxalis regnelli	Foliar spray	>33 mg/L	Miller unpublished
				Oxalis regnelli	Drench	0.25 mg/pot	Miller unpublished
				Ranunculus	Pre-plant dip	10-25 mg/L	Albrecht 1987
				Ranunculus	Drench	0.5 mg/pot	Albrecht 1987
				Tulipa	Drench	0.125-0.5 mg/pot	De Hertogh 1996
Daminozide	butanedioic acid mono (2,2 dimethylhydrazide)	B-Nine, Dazide	Powder, granular, 85%	*Ranunculus*	Foliar spray	5,000 mg/L	Albrecht 1987
Flurprimidol	α-(1-methylethyl)-α-[4-(trifluoromethoxy) phenyl]-5-pyrimidinemethanol	Topflor	Liquid, 0.38%	*Canna*	Foliar spray	15-30 mg/L	Bruner *et al*. 2001
				Crocosmia	Drench	0.25-1.5 mg/pot	Miller 2011
				Dahlia	Drench	< 1 mg/pot	Miller 2011
				Eucomis	Drench	1-3 mg/pot	Miller and Filios unpublished
				Hippeastrum	Pre-plant dip	100 mg/L	Miller *et al*. unpublished
				Hyacinthus	Pre-plant dip	20-25 mg/L	Krug *et al*. 2005a, 2005c; Miller 2011
				Hyacinthus	Drench	1-3 mg/pot	Krug *et al*. 2005a, 2005c; Miller 2011
				Lilium longiflorum	Drench	0.05-0.1 mg/pot	Miller unpublished
				Lilium hybrids	Pre-plant dip	1-50 mg/L	Krug *et al*. 2005b; Miller 2011
				Lilium hybrids	Drench	0.125-0.5 mg/pot	Krug *et al*. 2005b
				Narcissus sp.	Pre-plant dip		Krug *et al*. 2006a; Miller 2011
				Narcissus sp.	Drench	1-3 mg/pot	Krug *et al*. 2006a; Miller 2011
				Ranunculus	Pre-plant dip	3-10 mg/L	Albrecht 1987
				Tulipa	Drench	0.5-1 mg/pot	Miller 2011
				Zantedeschia	Pre-plant dip (experimenta l only)	50-100 mg/L	Miller 2011
				Zantedeschia	Drench	1.5-6 mg/pot	Miller 2011
Paclobutrazol	(±)-(R*,R*)-β-[(4-Chlorophenyl)methy]-α-(1,1-dimethylethyl)-I*H*-1,2,4-triazole-1-ethanol	Bonzi, Piccolo, Paczol, (also PP333)	Liquid, 0.4%	*Caladium*	Drench	0.5-1 mg/pot	Barrett *et al*. 1995
				Dahlia	Drench	4-8 mg/pot	Whipker and Hammer 1997
				Hippeastrum	Pre-plant dip	100-200 mg/L	Miller *et al*. unpublished
				Hyacinthus	Pre-plant dip	20-25 mg/L	Krug *et al*. 2005a; Miller 2011
				Hyacinthus	Drench	1-3 mg/pot	Krug *et al*. 2005a; Miller 2011
				Lachenalia	Pre-plant dip	50-200 mg/L	Ogutu and Miller unpublished
				Lachenalia	Drench	0.5-4 mg/pot	Ogutu and Miller unpublished
				Narcissus sp.	Pre-plant dip	20-25 mg/L	Krug *et al*. 2006a; Miller 2011
				Narcissus sp.	Drench	2-4 mg/pot, many cultivars are non-responsive	Krug *et al*. 2006a; Miller 2011
				Oxalis regnelli	Pre-plant dip	1-10 mg/L	Miller unpublished
				Oxalis regnelli	Foliar spray	<5 mg/L	Miller unpublished
				Oxalis regnelli	Drench	0.01-0.025 mg/pot	Miller unpublished
				Tulipa	Drench	1-2 mg/pot	De Hertogh 1996; Miller 2011
				Zantedeschia	Drench	1.5-6 mg/pot	Anonymous 2010; Miller 2011
				Zantedeschia	Pre-plant dip (experimenta l only)	100-200 mg/L	Miller 2011
Uniconazole	(E)(*S*)-1(4-chlorophenyl)4,4-dimethyl-2(1,2,4-triazol-1-yl)pent-1-ene-3-ol	Sumagic, Concise (also XE-1019)	Liquid 0.055 %	*Dahlia*	Drench	0.25-0.5 mg/pot	Whipker and Hammer 1997
				Hippeastrum	Pre-plant dip	25 mg/L	Miller *et al*. unpublished
				Lachenalia	Pre-plant dip	5-20 mg/L	Ogutu and Miller unpublished
				Lilium longiflorum	Foliar spray	1-15 mg/L	Bailey and Miller 1989a
				Lilium longiflorum	Drench	0.05-0.10 mg/pot	Miller 1992

Table 3 (Cont.)

Active ingredient	Chemical name	Trade name(s)	Formulation	Crop	Method of application	Rate	Reference
Anti-gibberellin growth retardants for height control (Cont.)							
				Lilium hybrids (asiatic, oriental, LA, etc.)	Pre-plant dip	1-10 mg/L	Miller 2011
				Lilium hybrids (asiatic, oriental, LA, etc.)	Foliar spray	2.5-10 mg/L	Valent USA 2011
				Lilium hybrids (Asiatic, Oriental, LA, etc.)	Drench	0.05-0.15 mg/pot	Bailey and Miller 1989b; Wilfret 1999
				Oxalis regnelli	Pre-plant dip	<0.5 mg/L	Miller unpublished
				Oxalis regnelli	Drench	<<0.025 mg/pot	Miller unpublished
				Zantedeschia	Pre-plant dip (experimental only)	5-15 mg/L	Miller 2011
Ethylene-releasing materials for height control							
Ethephon	(2-chloroethyl) phosphonic acid	Florel, Ethrel	Liquid, 3.9%	*Hyacinthus*	Foliar spray	500-2,500 mg/L	De Hertogh 1996; Krug *et al.* 2006a
				Hyacinthus	Drench	200-600 mg/L (experimental)	Miller unpublished
				Lilium hybrids (Asiatic, oriental, LA, etc.)	Drench	100-300 mg/L (experimental)	Miller unpublished
				Lilium (oriental hybrids)	Foliar spray[1]	1,000 mg/L	Chang and Miller 2007
				Narcissus sp.	Foliar spray	500-2,000 mg/L	De Hertogh 1996
				Narcissus sp.	Drench	200-500 mg/L (experimental)	Miller unpublished
				Narcissus tazetta	Foliar spray	2,000 mg/L	De Hertogh 1996
Anti-senescence treatments							
Gibberellin $_{4+7}$ and benzyladenine (1:1 concentration ratio)	N-(phenylmethyl)-1H-purine-6-amine plus gibberellins A_4A_7	Fascination, Fresco, Promalin	Liquid, 1.8% each component	*Lilium longiflorum*, asiatic, oriental and LA-hybrid lilies	Foliar spray	25-100 mg/L	Ranwala and Miller 1998
				Tulipa	Foliar spray	10-50 mg/L	Kim and Miller 2009
Treatments to increase flower numbers							
Gibberellin A_{4+7}	gibberellins A_4A_7	Provide	Liquid, 1.8%	*Zantedeschia*	Tuber spray	100 mg/L	Anonymous 2010
				Zantedeschia	Tuber dip	75 mg/L	Anonymous 2010
Gibberellic acid	Gibberellic acid (A_3)	ProGibb, florgib	Liquid, 4%	*Zantedeschia*	Tuber spray	125 mg/L	Anonymous 2010
				Zantedeschia	Tuber dip	100 mg/L; 500 mg/l	Corr and Widmer 1991; Anonymous 2010

[1] A side benefit of ethephon sprays on many oriental hybrid lilies is the near-elimination of Upper Leaf Necrosis in susceptible cultivars and larger bulb sizes.

days of moving into the greenhouse. Use rates for each chemical are given in **Table 3**. The drench should be applied 3-5 days after bringing plants into the greenhouse for mid-season forcings and 1-2 days after housing later in the season (De Hertogh 1996). The reason for the difference is the more rapid growth from later crops where a delay in late season application can result in reduced effect and taller plants.

An example of Bonzi effectiveness as a drench and interaction with cold duration is shown in **Fig. 1**. Numerous other examples and images of paclobutrazol and flurprimidol drenches on many tulip cultivars across cold weeks and years are available on the author's website (Miller 2012).

2. Hyacinth

While most hyacinths flower within the limits of the "aesthetic ratio", the very heavy flower stalks often topple over. As seen in **Fig. 5**, cultivar selection can help avoid this problem. Aside from cultivar, ethephon foliar sprays (500-2,000 mg/l) are commonly used for height control in hyacinths, and result in shorter, stockier flower stalks that are more resistant to toppling. The safe window for spraying ethephon is narrow: it should be sprayed when the plants are 7-10 cm tall, but the flowers should not show full color at spraying. Some cultivars require a second application (2-3 days after the first) to keep the flower stalks sufficiently short; be certain to consider this in relation to the timing of the first spray. If flowers are open, ethephon can cause premature senescence, an obviously undesirable situation. The material should be sprayed to runoff onto well-watered plants.

Growers occasionally report inadequate height control from ethephon spray applications. While no proven explanation exists, interactions with water quality used to prepare the spray has been hypothesized. As an alternative to ethephon sprays, pre-plant dips or soaks into flurprimidol have been shown to be very effective on hyacinth, and this method is currently increasing in popularity in the industry. As seen in **Fig. 6**, flurprimidol (20-30 mg/l) soaks for 5-30 min show excellent results. Miller (2012) gives extensive listings of cultivars, rates, and duration of pre-plant PGR soaks for hyacinths.

3. Narcissus

To date, many pot daffodils cultivars grown in North America are sprayed with 1,000-2,000 ppm ethephon when the leaves and/or flower stem are 7-10 cm long in the greenhouse. With some cultivars, and especially for late crops where plants have received excessive cold weeks, a second spray 2-3 days later is suggested. Specific use information

Table 4 Selected recipes for the preparation of PGR drench solutions for use on bulb crops grown in 10 or 15 cm pots. For a given does (mg/pot), note that because of less volume applied per pot, the concentration of drench solutions for smaller pots is actually greater than for larger pots.

Chemical and dose (mg per pot)	ppm of solution	Milliliters per liter of final solution
For 10 cm pots, apply 60 ml per pot		
Ancymidol		
0.125	2.1	7.9
0.25	4.2	15.8
0.5	8.4	31.6
1	16.7	63.1
Paclobutrazol		
0.5	8.3	2.1
1	16.7	4.2
1.5	25	6.3
2	33.3	8.3
Uniconazole		
0.1	1.7	3.3
0.2	3.4	6.6
0.3	5	10
0.4	6.7	13.3
Flurprimidol		
0.5	8.3	2.2
1	16.7	4.4
1.5	25	6.6
2	33.3	8.8
For 15 cm pots, apply 120 ml per pot		
Ancymidol		
0.125	1.1	3.9
0.25	2.1	7.9
0.5	4.2	15.8
1	8.3	31.6
Paclobutrazol		
0.5	4.2	1
1	8.3	2.1
1.5	12.5	3.1
2	16.7	4.2
Uniconazole		
0.1	0.8	1.7
0.2	1.7	3.4
0.3	2.5	5
0.4	3.4	6.7
Flurprimidol		
0.5	4.2	1.1
1	8.3	2.2
1.5	12.5	3.3
2	16.7	4.4

(ethephon concentration, number of sprays) for many cultivars is available (De Hertogh 1996). Increasingly, growers are realizing the actual need for narcissus height control lies in the postharvest phase; greenhouse height control is not needed. For postharvest, even "miniature" cultivars such as 'Tete-a-Tete' grow excessively and benefit from a PGR application (**Fig. 2**).

As with hyacinths, ethephon sprays can vary in effectiveness for unknown reasons and there has been interest in exploring alternative techniques for height control. Krug *et al.* (2006a) and Miller (2012) report on studies with pre-plant dips and rootzone drenches of paclobutrazol and flurprimidol. Both are effective and are being adopted in the industry. The main advantage of these materials (especially flurprimidol pre-plant dips) over ethephon sprays is longer lasting effect, so as to reduce the often excessive elongation of leaves and stems in the consumer environment (**Fig. 7**).

Non-rooting room crops

Lilium. Lilies are routinely treated with PGRs in North America. Since the mid-1970's, *L. longiflorum* (Easter lily) has been widely grown with rootzone and spray applications of ancymidol. Over the last *ca.* 20 years, uniconazole foliar sprays have been used, but unconfirmed reports of a phytotoxic effect (rubbery stems that bend over) have lessened uniconazole use over the last 5-7 years. Most recently, flurprimidol rootzone applications at very low rates (**Table 3**) have been adopted in the industry. Due to required concentrations in the 50-100 mg/l range, flurprimidol foliar sprays are not economically effective on Easter lily (Miller, unpublished data).

Within the wide range of hybrid lilies (mainly Asiatic, LA, Oriental, and newer hybrids; Van Tuyl and Arens 2011), PGR use has been nearly mandatory to produce acceptable pot plants, mainly since acceptable genetically dwarf cultivars have not been widely available. While this is changing, most hybrid lilies have been tailored to pots through a combination of pre-plant bulb dips (Ranwala *et al.* 2002) and (to a lesser extent) rootzone drenches and foliar sprays (**Table 3**).

Growth regulation strategies in specific hybrid groups is complicated by unique factors such as slow rooting relative to initial shoot growth (oriental hybrids) that prohibits effective uses of drenches, and shoot growth pattern (e.g. Oriental hybrids that cease shoot elongation when buds are small versus Asiatic and LA hybrids and *L. longiflorum* where shoot elongation continues until flowers open) (Ranwala *et al.* 2002). Suggested PGR rates for a wide variety of hybrid lilies are available online Miller (2012).

4. Narcissus tazetta (Paperwhite narcissus)

As with the cold-requiring narcissus, *N. tazetta* cultivars are commonly sprayed with ethephon at the same growth stage mentioned above. Undoubtedly, rootzone drenches and pre-plant bulb soaks with flurprimidol or paclobutrazol would also prove effective. For homeowner use, irrigating growing plants with 4-5% ethanol (diluted from, for example, gin, rum, whiskey, vodka, etc.) is effective in reducing excessive stem and leaf elongation without affecting flower number, size, longevity or fragrance (Miller and Finan 2006).

5. Hippeastrum

Hippeastrum (Amaryllis) plants are typically not treated with PGRs when forced as potted plants, although effective treatments, if available, would probably be adopted in the industry. Trials at Cornell suggest pre-plant bulb soaks in uniconazole, paclobutrazol and flurprimidol have promise (**Table 3**), but more work is needed. If successful, bulb soaks could potentially be useful for dry sale bulbs in pre-packaged consumer kits.

6. Zantedeschia

As a crop, the calla lily is rapidly increasing in popularity and cultivars vary a great deal in their need for chemical growth regulation. Over the last 15 years, paclobutrazol has been the main material used on callas, applied as a soil drench in the range of *ca.* 1-3 mg/pot (Anonymous 2010). Flurprimidol is also very effective at similar rates (Miller 2012).

7. Dahlia

De Hertogh (1996) gives extensive information on the use of ancymidol rootzone drenches on pot dahlia (grown from tuberous roots). While effective, ancymidol is an expensive chemical, especially at the required rates. More recently, trials with paclobutrazol and flurprimidol indicate their effectiveness as rootzone drenches (Whipker and Hammer 1997; Miller 2012).

STATUS OF PGR USE FOR NON-HEIGHT CONTROL USES ON BULB CROPS IN NORTH AMERICA

Increasing flower numbers

Zantedeschia tubers are routinely treated with gibberellins (tuber sprays or soaks) to reduce apical dominance and increase flower numbers when forced. A variety of gibberellins are used and concentrations are given in **Table 3**. Specific rates and methods exist per cultivar, and details are proprietary. A concern with *Zantedeschia* tuber treatments is the potential spread of Erwinia bacterial disease, so extreme care in handling tubers and inclusion of copper-containing fungicides is routine. Gibberellin treatments have been also adopted within the pot calla industry in The Netherlands.

Anti-senescence treatments

Giberellin$_{4+7}$ is a potent inhibitor of leaf senescence in many *Lilium* cultivars, and gibberellin also increases flower lifespan (Ranwala and Miller 1998). Across North America, *L. longiflorum* plants are routinely sprayed with giberellin$_{4+7}$ and the cytokinin, benzyladenine. Early research (Ranwala and Miller 1998) led to the identification of Promalin (a 1:1 mixture of giberellin$_{4+7}$ and benzyladenine) as an effective, commercially effective product. Intense industry interest in this material led to the registration of Fascination, a product identical to Promalin, but specifically labeled for use as an anti-senescence product in floricultural greenhouses (Valent USA 2009).

Control of Upper Leaf Necrosis (ULN) in Oriental hybrid lilies

Chang and Miller (2007) discovered a novel dual use for ethephon (as a foliar spray) in certain lily cultivars, that of inducing transient leaf epinasty to increase transpiration and reduce calcium deficiency leading to the physiological disorder, Upper Leaf Necrosis. A side benefit is a substantial degree of height control and thickening of stems from the ethephon treatment. At the present time, this is an unlabeled (non-registered) use of this product, although individual growers have trialed this method, and are enthusiastic about it.

FUTURE PROSPECTS FOR NORTH AMERICAN RESEARCH AND INDUSTRY

Flower bulbs can be expected to remain an important crop for North American greenhouse producers. Assuming larger issues such as plant health, product availability and market issues (production costs and profit) remain reasonably stable, the North American forcer will likely continue to force bulbs as part of the yearly mix.

This review has addressed a narrow but complex issue for bulb forcers, namely growth regulators. The prospects for continued use and availability of chemical PGRs in North America is good to excellent. There is strong grower acceptance of PGR technology and there is competition in the market place for making off-patent active ingredients available, and for the introduction of totally new active ingredients. This is not the case in many other parts of the world. Ultimately, public pressure can lead to changes in the *status quo* but for the foreseeable future, PGRs will continue to be used.

North American flower bulb PGR research is likely to continue along several fronts. First, continued evaluation of PGR effects on specific cultivars and forcing times (season or cold weeks) is essential for the major genera. Second, additional work is needed on PGR and environment interactions (especially temperature and light level) for the main spring bulbs (tulips, hyacinth and narcissus) and container-grown lilies. Third, it is likely that novel application methods will result in new ways to use PGRs, resulting in reduced cost to the grower, better plant quality and less chemical emission into the environment, for example soil applications of ethephon, which have proven very useful for narcissus and hyacinth (Miller, unpublished data). It is likely that the gibberellins and/or benzyladenine will find additional uses in delaying leaf or flower senescence in crops other than *Lilium.* Finally, new or underused crops may require PGR work to tailor them to size standards acceptable in the marketplace.

Funding of near-market, immediately useful PGR research will become increasingly difficult as profit margins are slim at most levels of the ornamentals industry. Regardless of the final research direction, it is inevitable that most such research will be funded by industry, whether it be chemical companies, grower or industry associations, or individual greenhouse companies.

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