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# Ethephon Substrate Drenches Control Stem Elongation of Containerized Herbaceous Perennials

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***Abstract.*** **Ethephon (2-chloroethylphosphonic acid) is a widely used plant growth regulator applied in the production of horticultural and agronomic crops. Preliminary research reports that drench applications inhibit growth of containerized ornamental plants, though few herbaceous perennials have been evaluated to determine responses to ethephon drenches. Therefore, our objective was to evaluate and quantify the efficacy of ethephon substrate drenches on the growth of 17 species of containerized flowering herbaceous perennials. Plants were transplanted into 12.7-cm or 16.5-cm containers filled with a soilless peat-based substrate. After 10 d, eight single-plant replicates received a substrate drench of 90 mL or 296 mL aliquots of solution, based on container size, containing 0, 125, 250, 500, 750, or 1000 mg·L$^{-1}$ ethephon. Plants were grown in a glass-glazed greenhouse for 3 to 8 weeks after drench before growth and morphological data, including plant height, plant diameter, shoot dry weight, and root dry weight were determined. The magnitude of growth control varied among herbaceous perennials species and ethephon concentrations. For most species, drenches of 125 to 500 mg·L$^{-1}$ ethephon were effective for controlling plant height and plant diameter without negatively affecting aesthetic ornamental plant quality. For instance, Russian sage (*Salvia yangii* B.T. Drew), wandflower [*Oenothera lindheimeri* (Engelm. & A. Gray) W.L. Wagner & Hoch 'Siskiyou Pink'], and blanket flower (*Gaillardia aristata* Pursh. 'SpinTop® Red Starburst') drenched with 125 and 250 mg·L$^{-1}$ were 48% to 56% (22.7 to 26.4 cm), 16% to 31% (6.9 to 13.2 cm), and 11% to 14% (2.1 to 2.6 cm) shorter, respectively, than untreated plants and no further height control occurred at concentrations >250 mg·L$^{-1}$ ethephon. We observed a 22% (9.5 cm) and a 35% (10.5 cm) smaller plant diameter for lobed tickseed (*Coreopsis auriculata* L. 'Leading Lady Iron') and pincushion flower (*Scabiosa columbaria* L. 'Pink Mist'), respectively, as concentrations increased from 0 to 125 mg·L$^{-1}$ ethephon. Root dry weight of lobed tickseed and woodland sage (*Salvia nemorosa* L. 'East Friesland') were 54% (8.2 cm) and 69% (6.2 cm) less, respectively, as concentrations increased from 0 to 500 mg·L$^{-1}$ ethephon. Although we did not quantify time to visible bud or open flower, most plants displayed visible buds or at least one open flower by the time data were collected; however, responses varied among species. Our research demonstrates that ethephon substrate drenches were effective in controlling growth of containerized herbaceous perennials, but growers must consider taxa-specific variations in response.**

In the United States, herbaceous perennials had a total sales value of USD $1.04 billion in 2023, making it the second largest sector of the floriculture market (US Department of Agriculture, National Agricultural Statistics Service 2024). Herbaceous perennials comprise a diverse group of plants with thousands of species in production, with a large diversity in cultivars, flower time, and cultural requirements (Grossman 2017). Blackeyed Susan (*Rudbeckia hirta* L.) typifies this diversity, with at least 74 cultivars exhibiting variations in flower color, mature size, and growth habit (Rich and Owen 2023). With this large variation of plant types, growth control during containerized greenhouse crop production is often needed to produce high-quality plants. Uncontrolled growth can increase the difficulty of growing and shipping many herbaceous perennials; however, growers can control excessive, undesirable growth in several ways. Manipulating environmental conditions such as light (intensity, quality, and photoperiod) and temperature (+DIF, –DIF, or DROP) or changing cultural practices like plant spacing (density), water stress, or restricting plant mineral nutrition can provide desired levels of growth control. Another method of controlling plant growth is to use plant growth regulators (PGRs).

PGRs are naturally or synthetically derived compounds that interfere with plant hormonal status to accelerate or reduce plant growth (Rademacher 2015; Sajjad et al. 2017). In the floriculture industry, PGRs are deployed widely to control internode elongation thereby producing a compact, uniform crop that meets ornamental market standards and are less likely to experience damage during shipping (Whipker and Latimer 2021). There are ∼40 unique growth-regulating active ingredients used to elicit a wide range of growth and developmental responses in cultivated crops (Rademacher 2015). Among these, 11 active ingredients are specifically labeled for use on ornamental crops, primarily to restrict stem elongation, but can also initiate rooting, promote stem elongation or lateral branching, and manipulate flowering (Owen 2024). In addition to variation in their effects on plants, PGRs can be applied using various methods, including foliar sprays, sprenches, substrate drenches, and pre-plant liner or bulb soaks (Krug 2004; Sajjad et al. 2017; Whipker and Latimer 2021). However, the efficacy of each PGR active ingredient varies with application method. For example, chlormequat chloride [(2-chloroethyl)trimethylammonium chloride] exhibits higher efficacy when applied as a foliar spray compared with a substrate drench due to its greater absorption through leaf tissue compared with root tissue (Owen 2024).

Among the PGR options for floriculture production, pyrimidine and triazole classified growth retardants are the most widely used to control growth, including ancymidol [cyclopropyl-(4-methoxyphenyl)-pyrimidin-5-ylmethanol], flurprimidol [2-methyl-1-pyrimidin-5-yl-1-[4-(trifluoromethoxy)phenyl]propan-1-ol], paclobutrazol [(2R, 3R)-1-(4-chlorophenyl)-4,4-dimethyl-2-(1,2,4-triazol-1-yl)pentan-3-ol], and uniconazole [(1E)-1-(4-chlorophenyl)-4,4-dimethyl-2-(1,2,4-triazol-1-yl)pent-1-en-3-ol] (Currey 2019; Owen 2024; Whipker and Latimer 2021). These chemicals control stem elongation by reducing gibberellic acid biosynthesis, the primary hormone responsible for cell elongation and division, and are known as gibberellin antagonists (Davies et al. 2017; Rademacher 2015). Ethephon (2-chloroethylphosphonic acid), while not a gibberellin antagonist, can provide growth control levels comparable to triazole PGRs in floriculture crops (Currey et al. 2016).

Ethephon is a PGR used for decades as a foliar spray to suppress plant height, increase lateral branching, and abort undesired flowers (Whipker and Latimer 2021). First introduced in 1973, ethephon was extensively researched in the 1990s, establishing its efficacy and applications as a PGR for floriculture crops (Konjoian 1995; Whipker 2014). Konjoian (1995) determined key factors affecting ethephon foliar spray efficacy and stability, including solution pH, water quality, and air temperature. It was previously thought that ethephon was not absorbed and translocated through root tissues, and thus had no root activity (Styer 2002). However, Miller et al. (2012) demonstrated ethephon substrate drenches significantly influenced time to flower, plant height, shoot dry weight (SDW), and root dry weight (RDW) in 11 cultivars of daffodil (*Narcissus* sp.) and 24 species of annual bedding plants, establishing the fact ethephon does have root activity. The authors also hypothesized the growth control was the result of ethylene generated by ethephon, rather than the result of reduced root growth. Subsequently, Miller et al. (2022) determined ethephon is translocated in xylem tissue, strengthening the hypothesis that growth control occurs through ethylene gas release in the substrate or plant tissues. Despite evidence of ethephon substrate drench effectiveness in annual

bedding and bulbous crops, research on its use in herbaceous perennials remains limited. Therefore, the objective of this research was to evaluate the efficacy of ethephon substrate drenches on growth control in 17 species of containerized herbaceous perennials and determine optimal application concentrations.

## Materials and Methods

*Plant material.* On 19 Jul 2023 (Expt. 1), unrooted shoot-tip cuttings of lobed tickseed (*Coreopsis auriculata* L. 'Leading Lady Iron'), tender foxglove (*Digiplexis ×hybrida* 'Berry Canary'), spotted deadnettle (*Lamium maculatum* L. 'Purple Dragon'), scarlet beebalm (*Monarda didyma* L. 'Pocahontas Red'), Russian sage [*Salvia yangii* B.T. Drew (formerly known as *Perovskia atriplicifolia* Benth.)] and wandflower [*Oenothera lindheimeri* (Engelm. & A. Gray) W.L. Wagner & Hoch 'Siskiyou Pink' (formerly known as *Gaura lindheimeri*)] were received from a commercial cutting supplier (Dümmen Orange NA, Hilliard, OH, USA). On 12 Sep (Expt. 2), unrooted shoot-tip cuttings of blanket flower (*Gaillardia aristata* Pursh. 'SpinTop® Red Starburst'), pincushion flower (*Scabiosa columbaria* L. 'Pink Mist'), Shasta daisy [*Leucanthemum maximum* (Ramond) DC. 'Snow Cap'], wallflower (*Erysimum ×hybrida* 'WallArt Citric'), and woodland sage (*Salvia nemorosa* L. 'East Friesland') were received from a commercial cutting supplier (Dümmen Orange NA). On 12 Dec (Expt. 3), unrooted shoot-tip cuttings of catmint (*Nepeta faassenii* E. Morren & Decne. 'Walkers Low'), evening

Table 1. Average photosynthetic daily light integral (DLI), calculated vapor pressure deficit (VPD), and canopy air temperature during propagation and toning of 17 herbaceous perennial species {Expt. 1: Lobed tickseed (*Coreopsis auriculata* L. 'Leading Lady Iron'), tender foxglove (*Digiplexis ×hybrida* 'Berry Canary'), spotted deadnettle (*Lamium maculatum* L. 'Purple Dragon'), scarlet beebalm (*Monarda didyma* L. 'Pocahontas Red'), Russian sage (*Salvia yangii* B.T. Drew) and wandflower [*Oenothera lindheimeri* (Engelm. & A. Gray) W.L. Wagner & Hoch 'Siskiyou Pink']; Expt. 2: blanket flower (*Gaillardia aristate* Pursh. 'SpinTop® Red Starburst'), pincushion flower (*Scabiosa columbaria* L. 'Pink Mist'), Shasta daisy [*Leucanthemum maximum* (Ramond) DC. 'Snow Cap'], wallflower (*Erysimum ×hybrida* 'WallArt Citric'), and woodland sage (*Salvia nemorosa* L. 'East Friesland'); and Expt. 3: catmint (*Nepeta faassenii* E. Morren & Decne. 'Walkers Low'), evening primrose (*Oenothera speciosa* Nutt. 'Twilight'), garden phlox (*Phlox paniculata* L. 'Flame Red'), iceplant [*Delosperma cooperi* (Hook. f.) L. Bolus 'Jewel of Desert Ruby'], showy stonecrop (*Sedum lineare* Thunb. 'Autumn Fire'), and verbena (*Verbena canadensis* L. 'Homestead Purple')}. Unrooted cuttings were propagated, and young plants were toned in a glass-glazed greenhouse for a total of 28 d under ambient daylight supplemented with ≈120 μmol·m$^{-2}$·s$^{-1}$ from 1000-W light-emitting diode lamps from 0600 to 2200 HR (16-h photoperiod) to maintain a DLI of 10 or 14 mol·m$^{-2}$·d$^{-1}$. The canopy air temperature and root zone heating setpoints were 23 °C.

| Herbaceous perennials | DLI (mol·m$^{-2}$·d$^{-1}$) | VPD (kPa) | Canopy air temp (°C) |
|---|---|---|---|
| Expt. 1 | | | |
| Lobed tickseed | 10.9 ± 7.0 | 1.7 ± 0.7 | 20.6 ± 1.8 |
| Tender foxglove | | | |
| Spotted henbit | | | |
| Scarlet beebalm | | | |
| Russian sage | | | |
| Wandflower | | | |
| Expt. 2 | | | |
| Blanket flower | 12.8 ± 0.8 | 1.8 ± 0.6 | 21.4 ± 0.9 |
| Pincushion flower | | | |
| Shasta daisy | | | |
| Wallflower | | | |
| Woodland sage | | | |
| Expt. 3 | | | |
| Catmint | 10.7 ± 1.6 | 1.7 ± 0.6 | 21.0 ± 0.7 |
| Evening primrose | | | |
| Garden phlox | | | |
| Iceplant | | | |
| Showy stonecrop | | | |
| Verbena | | | |

Table 2. Average photosynthetic daily light integrals (DLIs), relative humidity (RH), and canopy air temperature during finishing of 17 herbaceous perennial species {Expt. 1: lobed tickseed (*Coreopsis auriculata* L. 'Leading Lady Iron'), tender foxglove (*Digiplexis ×hybrida* 'Berry Canary'), spotted deadnettle (*Lamium maculatum* L. 'Purple Dragon'), scarlet beebalm (*Monarda didyma* L. 'Pocahontas Red'), Russian sage (*Salvia yangii* B.T. Drew) and wandflower [*Oenothera lindheimeri* (Engelm. & A. Gray) W.L. Wagner & Hoch 'Siskiyou Pink']; Expt. 2: blanket flower (*Gaillardia aristata* Pursh. 'SpinTop® Red Starburst'), pincushion flower (*Scabiosa columbaria* L. 'Pink Mist'), Shasta daisy [*Leucanthemum maximum* (Ramond) DC. 'Snow Cap'], wallflower (*Erysimum ×hybrida* 'WallArt Citric'), and woodland sage (*Salvia nemorosa* L. 'East Friesland'); and Expt. 3: catmint (*Nepeta faassenii* E. Morren & Decne. 'Walkers Low'), evening primrose (*Oenothera speciosa* Nutt. 'Twilight'), garden phlox (*Phlox paniculata* L. 'Flame Red'), iceplant [*Delosperma cooperi* (Hook. f.) L. Bolus 'Jewel of Desert Ruby'], showy stonecrop (*Sedum lineare* Thunb. 'Autumn Fire'), and verbena (*Verbena canadensis* L. 'Homestead Purple')}. Plants were transplanted into 12.7-cm (946 mL) or 16.5-cm (1.7 L) containers filled with a peat-based substrate and grown in a glass-glazed greenhouse under ambient daylight supplemented with ≈120 μmol·m$^{-2}$·s$^{-1}$ from 1000-W light-emitting diode lamps from 0600 to 2200 HR (16-h photoperiod) to maintain a DLI of 10 to 14 mol·m$^{-2}$·d$^{-1}$. Canopy air temperature setpoint was 20 °C.

| Herbaceous perennials | DLI (mol·m$^{-2}$·d$^{-1}$) | RH (%) | Air temp (°C) |
|---|---|---|---|
| Expt. 1 | | | |
| Lobed tickseed | 13.6 ± 1.7 | 64.0 ± 22.2 | 22.0 ± 3.1 |
| Tender foxglove | | | |
| Spotted deadnettle | 14.1 ± 1.8 | 68.5 ± 21.3 | 22.6 ± 3.2 |
| Scarlet beebalm | 13.9 ± 1.8 | 65.9 ± 22.7 | 22.3 ± 3.2 |
| Russian sage | | | |
| Wandflower | | | |
| Expt. 2 | | | |
| Blanket flower | 11.6 ± 0.8 | 44.5 ± 20.2 | 20.3 ± 5.8 |
| Pincushion flower | 11.5 ± 0.9 | 43.5 ± 19.1 | 20.4 ± 5.6 |
| Shasta daisy | | | |
| Wallflower | 12.1 ± 0.8 | 49.6 ± 23.8 | 19.5 ± 5.3 |
| Woodland sage | 11.5 ± 0.9 | 43.5 ± 19.1 | 20.4 ± 5.6 |
| Expt. 3 | | | |
| Catmint | 9.4 ± 1.6 | 50.7 ± 1.1 | 20.8 ± 0.2 |
| Evening primrose | | | |
| Garden phlox | 9.7 ± 1.6 | 49.9 ± 1.3 | 20.7 ± 0.4 |
| Iceplant | 9.2 ± 1.6 | 49.5 ± 1.1 | 20.8 ± 0.1 |
| Showy stonecrop | 9.7 ± 2.0 | 49.9 ± 1.3 | 20.7 ± 0.4 |
| Verbena | 9.7 ± 1.8 | 49.2 ± 1.3 | 20.9 ± 0.2 |

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primrose (*Oenothera speciosa* Nutt. 'Twilight'), garden phlox (*Phlox paniculata* L. 'Flame Red'), iceplant [*Delosperma cooperi* (Hook. f.) L. Bolus 'Jewel of Desert Ruby'], showy stonecrop (*Sedum lineare* Thunb. 'Autumn Fire'), and verbena (*Verbena canadensis* L. 'Homestead Purple') were received from a commercial cutting supplier (Dümmen Orange NA).

*Propagation, culture, and environment.* On receipt, cuttings of each species were individually inserted into industry-standard, 72-cell propagation trays (33-mL individual cell volume, 54 cm × 28 cm × 5 cm; Grower Select®, BFG Supply, Burton, OH, USA). Propagation trays were filled with a pre-moistened propagation substrate formulated with 50:50 (v/v) commercial soilless substrate composed of (by vol.) 75% Canadian sphagnum peatmoss, 25% perlite, dolomitic lime, a nutrient starter charge, and a wetting agent (Sunshine Mix No. 1; Sun Gro Horticulture, Agawam, MA, USA) and 50% coarse perlite (Coarse Perlite; Sun Gro Horticulture). Propagation substrate physical properties were determined using three representative samples that were analyzed according to the North Carolina State University Porometer Procedure (Fonteno et al. 1995). Physical properties of the propagation substrate were (by vol.) 14% ± 1.2% air space, 78% ± 1.1% total porosity, 64% ± 0.3% container capacity, and 0.09% ± 0.1 g·cm$^{-3}$ bulk density. Before cutting insertion, propagation trays were irrigated to container capacity and allowed to drain.

Propagation trays of each species were placed in a propagation environment in a glass-glazed greenhouse (70 m$^2$; 16.5 m × 7.3 m) at The Ohio State University Controlled Environment Agriculture Research Complex, Columbus, OH, USA (lat. 40°N, 83°W; 238 m above sea level) equipped with two exhaust fans, evaporative-pad cooling, a vertical air flow fan, retractable shade and energy curtains, and heat provided from a hot water boiler, all controlled by an environmental computer system (Priva B.V., ver. 9.7, De Lier, Netherlands). Vertical air flow speed was measured at 24 points across the greenhouse environment with a handheld hotwire anemometer (Model A004; Kanomax Japan, Inc., Osaka, Japan) and averaged 0.07 ± 0.02 m·s$^{-1}$. Ambient carbon dioxide ($CO_2$) in the greenhouse environment was measured at 24 points across the greenhouse with a handheld $CO_2$ meter (Model GM70; Vaisala, Helsinki, Finland) and averaged 472.9 ± 23.5 µmol·mol$^{-1}$. No supplemental $CO_2$ was provided throughout any of the experiments conducted.

The propagation bench (6.0 m × 1.5 m) was elevated 0.86 m above the greenhouse floor and oriented with a latitudinal axis running east–west. The expanded metal bench was insulated with cellofoam expanded polystyrene boards faced with a reflective foil (1.2 m × 2.4 m × 2.3 cm; Polyshield®, Whiteland, IN, USA) and covered with bench-top root zone heating mats (Redi-Heat™ Heavy-Duty Propagation Mats; Phytotronics Inc., Earth City, MO, USA). Each heating mat

Table 3. Regression equations (see Figs. 7–9) for plant height, plant diameter, shoot dry weight, and root dry weight of 17 herbaceous perennial species {Expt. 1: lobed tickseed (*Coreopsis auriculata* L. 'Leading Lady Iron'), tender foxglove (*Digiplexis ×hybrida* 'Berry Canary'), spotted deadnettle (*Lamium maculatum* L. 'Purple Dragon'), scarlet beebalm (*Monarda didyma* L. 'Pocahontas Red'), Russian sage (*Salvia yangii* B.T. Drew), and wandflower [*Oenothera lindheimeri* (Engelm. & A. Gray) W.L. Wagner & Hoch 'Siskiyou Pink']; Expt. 2: blanket flower (*Gaillardia aristata* Pursh. 'SpinTop® Red Starburst'), pincushion flower (*Scabiosa columbaria* L. 'Pink Mist'), Shasta daisy [*Leucanthemum maximum* (Ramond) DC. 'Snow Cap'], wallflower (*Erysimum ×hybrida* 'WallArt Citric'), and woodland sage (*Salvia nemorosa* L. 'East Friesland'); and Expt. 3: catmint (*Nepeta faassenii* E. Morren & Decne. 'Walkers Low'), evening primrose (*Oenothera speciosa* Nutt. 'Twilight'), garden phlox (*Phlox paniculata* L. 'Flame Red'), iceplant [*Delosperma cooperi* (Hook. f.) L. Bolus 'Jewel of Desert Ruby'], showy stonecrop (*Sedum lineare* Thunb. 'Autumn Fire'), and verbena (*Verbena canadensis* L. 'Homestead Purple')}.

| Herbaceous perennials | Figure | Height (cm) | Figure | Diam (cm) | Figure | SDW (g) | Figure | RDW (g) |
|---|---|---|---|---|---|---|---|---|
| Expt. 1 | | | | | | | | |
| Lobed tickseed | 7A | $y = 32.737 - 0.009x$[i] | 7G | $y = 47.750 - 0.003x - 7.380x^2$ | 7M | $y = 20.412 - 0.006x - 4.537x^2$ | 7S | $y = 14.957 - 0.007x - 4.076x^2$ |
| Tender foxglove | 7B | $y = 24.825 - 0.014x + 10.76x^2$ | 7H | $y = 39.325 - 0.005x - 3.371x^2$ | 7N | $y = 30.738 - 0.010x - 6.804x^2$ | 7T | $y = 37.813 - 0.030x + 5.165x^2$ |
| Spotted henbit | 7C | $y = 18.125 - 0.002x - 7.459x^2$ | 7I | $y = 44.568 - 0.006x - 15.527x^2$ | 7O | $y = 11.330 - 0.002x - 4.983x^2$ | 7U | $y = 9.858 - 0.001x - 5.174x^2$ |
| Scarlet beebalm | 7D | $y = 22.400 - 0.004x - 4.908x^2$ | 7J | $y = 23.675 - 0.008x - 6.762x^2$ | 7P | $y = 8.230 - 0.001x - 4.009x^2$ | 7V | $y = 12.017 - 0.001x - 6.816x^2$ |
| Russian sage | 7E | $y = 46.600 - 0.011x - 22.292x^2$ | 7K | $y = 40.987 - 0.011x - 17.439x^2$ | 7Q | $y = 8.220 - 0.002x - 4.724x^2$ | 7W | $y = 4.966 - 0.002x - 0.635x^2$ |
| Wandflower | 7F | $y = 41.887 - 0.009x - 8.199x^2$ | 7L | $y = 59.593 - 0.019x$ | 7R | $y = 21.200 - 0.009x$ | 7X | $y = 10.336 - 0.009x + 6.276x^2$ |
| Expt. 2 | | | | | | | | |
| Blanket flower | 8A | $y = 18.087 - 0.007x + 0.000004x^2$ | 8F | $y = 24.424 - 0.011x + 0.00001x^2$ | 8K | $y = 6.237 - 0.003x + 0.000001x^2$ | 8P | $y = 10.699 - 0.013x + 0.000007x^2$ |
| Pincushion flower | 8B | $y = 46.187 - 0.124x + 0.00008x^2$ | 8G | $y = 28.083 - 0.028x + 0.00001x^2$ | 8L | $y = 17.523 - 0.032x + 0.00002x^2$ | 8Q | $y = 16.001 - 0.038x + 0.00002x^2$ |
| Shasta daisy | 8C | $y = 19.136 - 0.007x + 0.000003x^2$ | 8H | $y = 25.182 - 0.011x + 000007x^2$ | 8M | $y = 9.284 - 0.006x + 0.000003x^2$ | 8R | $y = 12.262 - 0.013x + 0.000005x^2$ |
| Wallflower | 8D | $y = 15.100 - 0.079x$ | 8I | $y = 25.457 - 0.142x$ | 8N | $y = 9.563 - 0.065x$ | 8S | —[ii] |
| Woodland sage | 8E | $y = 37.784 - 0.030x + 0.000007x^2$ | 8J | $y = 21.034 - 0.021x + 0.00001x^2$ | 8O | $y = 5.590 - 0.005x + 0.000002x^2$ | 8T | $y = 8.016 - 0.016x + 0.00001x^2$ |
| Expt. 3 | | | | | | | | |
| Catmint | 9A | $y = 19.100 - 0.031x + 0.00002x^2$ | 9G | $y = 32.925 - 0.056x + 0.00003x^2$ | 9M | $y = 2.895 - 0.005x + 0.000004x^2$ | 9S | $y = 3.840 - 0.005x + 0.000004x^2$ |
| Evening primrose | 9B | $y = 19.616 - 0.012x + 0.000005x^2$ | 9H | $y = 22.947 - 0.020x + 0.00001x^2$ | 9N | $y = 5.369 - 0.005x + 0.000003x^2$ | 9T | $y = 4.550 - 0.002x + 0.0000007x^2$ |
| Garden phlox | 9C | $y = 23.952 - 0.028x + 0.00001x^2$ | 9I | $y = 15.762 - 0.019x + 0.00001x^2$ | 9O | $y = 4.283 - 0.008x + 0.000005x^2$ | 9U | $y = 3.372 - 0.007x + 0.000004x^2$ |
| Iceplant | 9D | NS[iii] | 9J | NS | 9P | NS | 9V | NS |
| Showy stonecrop | 9E | $y = 21.049 - 0.019x + 0.00001x^2$ | 9K | $y = 20.303 - 0.026x + 0.00001x^2$ | 9Q | $y = 8.173 - 0.015x + 0.00001x^2$ | 9W | $y = 5.687 - 0.010x + 0.000007x^2$ |
| Verbena | 9F | NS | 9L | $y = 14.698 - 0.022x + 0.00001x^2$ | 9R | $y = 1.231 - 0.0004x$ | 9X | $y = 0.493 - 0.0006x + 0.0000004x^2$ |

[i] Linear ($y = a + bx$) or quadratic ($y = a + bx + cx^2$) equations for each parameter.
[ii] No data recorded.
[iii] Nonsignificant (NS).

was controlled independently with a thermostat (RDT-4 Thermostat; Phytotronics Inc.) and set to maintain a root zone temperature of 23 °C. To prevent heat loss and moisture accumulation, the propagation bench was covered with a 4-mil black construction film (3.0 m × 30.5 m roll; Blue Hawk, Poly-America, Grand Prairie, TX, USA). A propagation tent (6.0 m × 1.5 m × 1.5 m) was constructed with 1.9-cm diameter polyvinyl chloride pipe (Charlotte Piper and Foundry Co., Charlotte, NC, USA) and covered with fixed 4-mil clear construction film (3 m × 30.5 m roll; Blue Hawk) and a woven shadecloth providing ≈56% shade (Solaro 5620 O-R-FR; Ludvig Svensson, Inc., Charlotte, NC, USA).

Beginning at placement of cuttings under propagation conditions, mist consisting of clear tap water was controlled (Super Nova 12B mist controller; Phytotronics, Inc.) and applied for 6 s every 10 min beginning and ending 2 h before and after the photoperiod. After 1 d, mist was suspended from 0900 to 0930 HR to allow surfaces of the unrooted cuttings to dry. A foliar rooting hormone solution containing deionized water and indole-3-butric acid [20% IBA (Advocate®); Fine Americas, Walnut Creek, CA, USA] was applied and delivered 200 mg·L$^{-1}$ IBA at 0.20 L·m$^{-2}$ uniformly across propagation trays. Cuttings were allowed to dry, and mist resumed at 1030 HR.

Upon visible adventitious root formation (roots ≥ 5 mm in length), cuttings of each species were removed from the propagation bench and transferred to an adjacent expanded metal bench for subsequent rooting. On transfer, cuttings were overhead irrigated once daily with clear tap water supplemented with a water-soluble fertilizer [15 nitrogen (N)–2.2 phosphorous (P)–12.5 potassium (K)–4 calcium (Ca)–2 magnesium (Mg); 15–5–15 Ca-Mg Jack's Professional Pure Water XL; J.R. Peters Inc., Allentown, PA, USA] containing 3% ammoniacal-N and 12% nitrate-N delivered by an injector (Model D25RE2; 0.05 to 11 GPM Dosatron; Dosatron International, LLC, Clearwater, FL, USA). Young plants received the following (mg·L$^{-1}$): 150 N, 21.5 P, 124.5 K, 40 Ca, 20 Mg, 0.15 boron (B), 0.13 sulfur (S), 0.08 copper (Cu), 0.75 iron (Fe), 0.38 manganese (Mn), 0.08 molybdenum (Mo), and 0.38 zinc (Zn). After 1 week of adventitious root development, young plants received a magnesium sulfate (J.R. Peters Inc.) drench providing 11.7 mg·L$^{-1}$ Mg and 15.4 mg·L$^{-1}$ S.

Supplemental and day-extension lighting was provided by 1000-W light-emitting diode lamps (Gavita CT1930e LED 120 to 277 V; Gavita Horticultural Lighting, Amsterdam, Netherlands) from 0600 to 2200 HR (16-h photoperiod) that delivered a supplemental photosynthetic photon flux density of ≈120 µmol·m$^{-2}$·s$^{-1}$ at cutting height [as measured with a quantum sensor (LI-250A light meter; LI-COR Biosciences, Lincoln, NE, USA)]. Light-emitting diode lamps were controlled by an environmental computer system (Priva B.V., ver. 9.7) and turned on when the outdoor light intensity fell below ≈300 µmol·m$^{-2}$·s$^{-1}$ and turned off when the outdoor

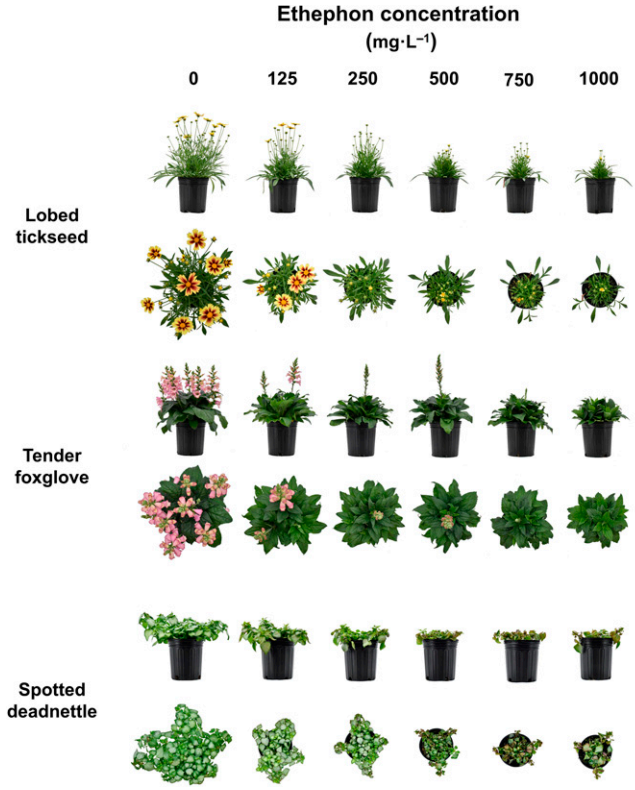


Fig. 1. Depiction of lobed tickseed (*Coreopsis auriculata* L. 'Leading Lady Iron'), tender foxglove (*Digiplexis* ×*hybrida* 'Berry Canary'), and spotted deadnettle (*Lamium maculatum* L. 'Purple Dragon') grown in 16.5-cm containers (1.7 L) filled with a commercial soilless peat-based substrate and drenched with 296 mL aliquots of a solution containing 0, 125, 250, 500, 750, or 1000 mg·L$^{-1}$ ethephon at 10 d after transplant. Photographs were taken 6, 6, and 3 weeks after drench for lobed tickseed, tender foxglove, and spotted deadnettle, respectively.

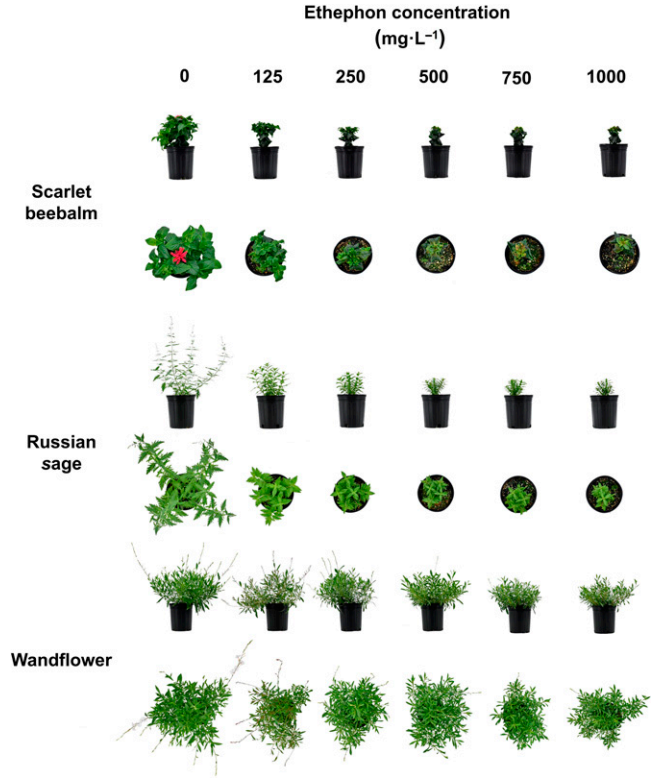


Fig. 2. Depiction of scarlet beebalm (*Monarda didyma* L. 'Pocahontas Red'), Russian sage (*Salvia yangii* B.T. Drew), and wandflower [*Oenothera lindheimeri* (Engelm. & A. Gray) W.L. Wagner & Hoch 'Siskiyou Pink'] grown in 16.5-cm containers (1.7 L) filled with a commercial soilless peat-based substrate and drenched with 296 mL aliquots of a solution containing 0, 125, 250, 500, 750, or 1000 mg·L$^{-1}$ ethephon at 10 d after transplant. Photographs were taken 4 weeks after drench.

light intensity reached ≈500 µmol·m$^{-2}$·s$^{-1}$. Dual layer retractable woven shade curtains were deployed when the outdoor light intensity reached ≈750 µmol·m$^{-2}$·s$^{-1}$ and retracted when the outdoor light intensity fell below ≈600 µmol·m$^{-2}$·s$^{-1}$. The top retractable woven shade curtains (Luxous 1547 D FR; Ludvig Svensson Inc.) were deployed to 70% and the bottom layer (Harmony 4647 FR; Ludvig Svensson Inc.) were deployed to 100%. Vertical retractable woven light spill curtains (Obscura 10070 R FR W; Ludvig Svensson Inc.) were deployed from 1700 to 0800 HR.

Full-spectrum quantum sensors (SQ-500; Apogee Instruments, Logan, UT, USA) measured photosynthetic photon flux density at plant canopy level. Canopy air temperature and relative humidity (RH) were measured using a precision thermistor (ST-110-SS; Apogee Instruments) and humidity probe (EE08-SS; Apogee Instruments), respectively, encased in a fan-aspirated solar radiation shield (TS-130-SS; Apogee Instruments). Measurements were recorded every 15 s and the average for each sensor was logged every 15 min by a data logger (Model CR1000X; Campbell Scientific, Inc., Logan, UT, USA). Greenhouse air temperature and RH set points were 23 °C and 80%, respectively. Environmental data during propagation and toning phases of each species during Expts. 1, 2, and 3 are reported in Table 1. Vapor pressure deficit was calculated from greenhouse air temperature and RH averages.

*Plant culture and environment.* In all experiments, 28-d-old young plants with similar heights, stem calipers, and node and leaf numbers were selected. On 16 Aug (Expt. 1), lobed tickseed, tender foxglove, spotted deadnettle, scarlet beebalm, Russian sage, and wandflower were transplanted with one plant per 16.5-cm diameter container (1.7 L volume, C300; Nursery Supplies, Inc., Chambersburg, PA, USA). On 12 Sep (Expt. 2), blanket flower, Shasta daisy, wallflower, woodland sage, and pincushion flower were transplanted with one plant per 16.5-cm diameter container (1.7 L volume, C300). On 9 Jan 2024 (Expt. 3), iceplant, catmint, evening primrose, garden phlox, showy stonecrop, and verbena were transplanted with one plant per 12.7-cm diameter container (946-mL volume; East Jordan Plastics, Inc.; East Jordan, MI, USA). All containers were filled with a pre-moistened commercial soilless substrate (Sunshine Mix No. 1; Sun Gro Horticulture). Substrate physical properties were determined using procedures previously described by Fonteno et al. (1995) and were (by vol.) 15.2% ± 1.1% air space, 84.1% ± 0.8% total porosity, 68.9% ± 1.3% container capacity, and 5.3 ± 0.2 g·cm$^{-3}$ bulk density.

On transplant, plants were overhead irrigated to container capacity with clear tap water. At each subsequent irrigation, plants were overhead irrigated with clear tap water supplemented with a water-soluble fertilizer as previously described. At 14 d after transplant, plants were irrigated with magnesium

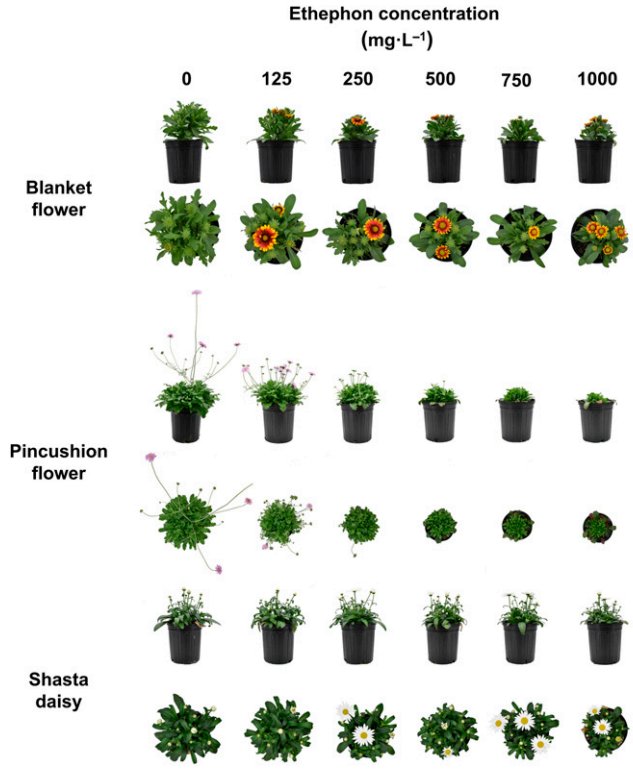


Fig. 3. Depiction of blanket flower (*Gaillardia aristata* Pursh. 'SpinTop® Red Starburst'), pincushion flower (*Scabiosa columbaria* L. 'Pink Mist'), and Shasta daisy [*Leucanthemum maximum* (Ramond) DC. 'Snow Cap'] grown in 16.5-cm containers (1.7 L) filled with a commercial soilless peat-based substrate and drenched with 296 mL aliquots of a solution containing 0, 125, 250, 500, 750, or 1000 mg·L$^{-1}$ ethephon at 10 d after transplant. Photographs were taken 5, 8, and 7 weeks after drench for blanket flower, pincushion flower, and Shasta daisy, respectively.

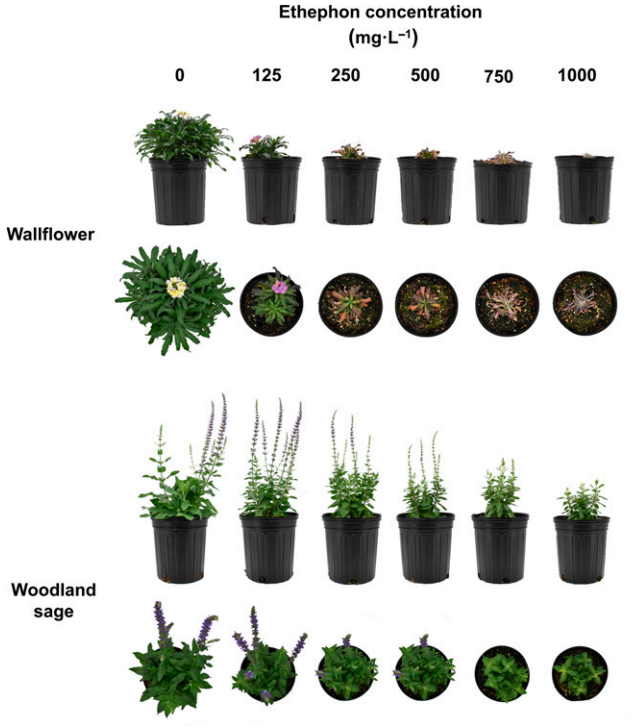


Fig. 4. Depiction of wallflower (*Erysimum ×hybrida* 'WallArt Citric') and woodland sage (*Salvia nemorosa* L. 'East Friesland') grown in 16.5-cm containers (1.7 L) filled with a commercial soilless peat-based substrate and drenched with 296 mL aliquots of a solution containing 0, 125, 250, 500, 750, or 1000 mg·L$^{-1}$ ethephon at 10 d after transplant. Photographs were taken 6 and 7 weeks after drench for wallflower and woodland sage, respectively.

sulfate (J.R. Peters Inc.) as previously described.

Except where indicated, the greenhouse environment, setpoints, and monitoring were the same as described in propagation. Plants were grown on expanded metal benches (6.0 m × 1.5 m) elevated 0.86-m above the greenhouse floor and oriented with a latitudinal axis running east–west in a glass-glazed greenhouse. Light-emitting diode lamps were controlled by an environmental computer system (Priva B.V., ver. 9.7) and turned on when the outdoor light intensity fell below ≈250 μmol·m$^{-2}$·s$^{-1}$ and turned off when the outdoor light intensity reached ≈700 μmol·m$^{-2}$·s$^{-1}$ and greenhouse air temperature set point was 20 °C. Environmental data collected during plant culture for each species during Expts. 1, 2, and 3 are reported in Table 2.

*Ethephon substrate drenches.* Ten days after transplant, eight single-plant replicates (individual plants) of each species received ethephon substrate drenches that were applied from 0900 to 1200 HR. For Expts. 1 and 2, plants grown in 16.5-cm diameter containers were drenched with 296-mL aliquots of solution containing deionized water (0 mg·L$^{-1}$; control) or 125, 250, 500, 750, or 1000 mg·L$^{-1}$ ethephon (Collate® 2L; Fine Americas, Inc.) (0, 36.9, 73.9, 147.9, 221.8, and 295.7 mg a.i./pot). For Expt. 3, plants grown in 12.7-cm diameter containers were drenched with 90-mL aliquots of solution containing deionized water (0 mg·L$^{-1}$; control) or increasing concentrations of ethephon as previously mentioned.

*Substrate pH management.* At 7 d before ethephon drench application and 2 and 7 d after drench application, substrate solution was extracted 1 h after irrigation using the Pour-Thru method (Cavins 2002) and analyzed for pH and electrical conductivity (EC) using a handheld pH and EC meter (HI 9813-6; Hanna Instruments, Woonsocket, RI, USA). Average initial substrate pH before ethephon drench application was 5.8 ± 0.1. At 2 d after ethephon drench application, substrate pH was determined to be 5.5 ± 0.1; however, at 7 d after drench application, substrate pH returned to 5.8 ± 0.2 (data not shown). No low substrate pH induced nutrient disorder symptomologies were observed for any species grown during Expts. 1, 2, and 3.

*Data collection, calculations, and observations.* Throughout each experiment, visual observations were recorded for any phytotoxic effects. The experiments were terminated, and the plants were harvested 3 (iceplant and spotted deadnettle), 4 (catmint, evening primrose, Russian sage, scarlet beebalm, and wandflower), 5 (blanket flower and verbena), 6 (erysimum, garden phlox, lobed tickseed, showy stonecrop, and tender foxglove), 7 (Shasta daisy and woodland sage), or 8 (pincushion) weeks after drench. At termination, plant height and plant diameter were determined. Plant height was measured from the substrate surface to the highest growing point of the plant. Plant diameter was determined by measuring the widest dimension and the axis perpendicular to the widest dimension and averaging. Plants with at least one open flower (reflexed petals with

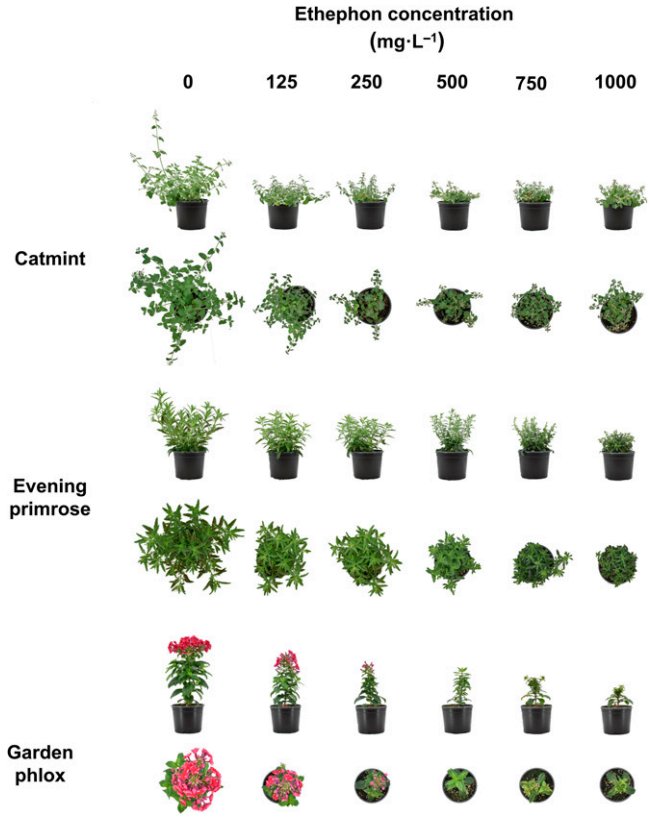


Fig. 5. Depiction of catmint (*Nepeta faassenii* E. Morren & Decne. 'Walkers Low'), evening primrose (*Oenothera speciosa* Sims. 'Twilight'), and garden phlox (*Phlox paniculata* L. 'Flame Red') grown in 12.7-cm containers filled with soilless peat-based substrate and drenched with 90 mL aliquots of a solution containing 0, 125, 250, 500, 750, or 1000 mg·L$^{-1}$ ethephon at 10 d after transplant. Photographs were taken 4, 4, and 6 weeks after drench for catmint, evening primrose, and garden phlox, respectively.

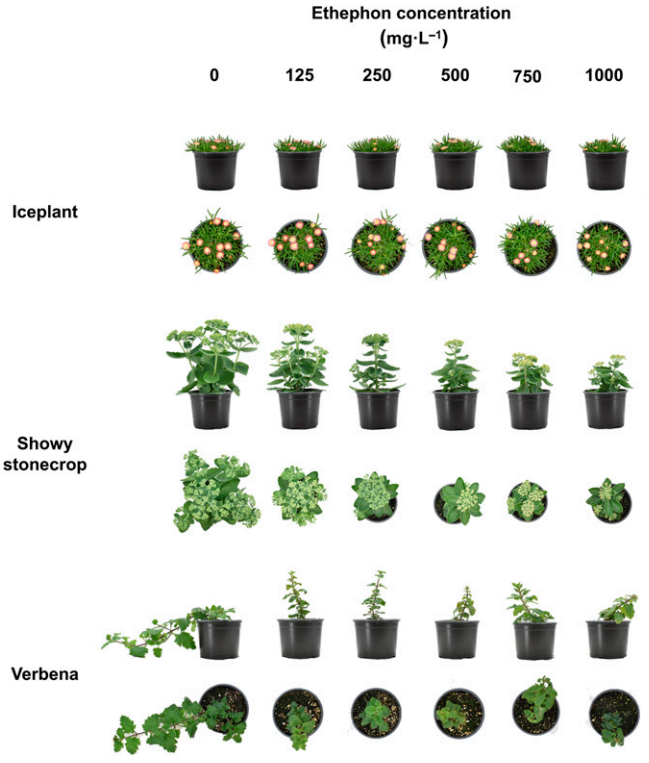


Fig. 6. Depiction of iceplant [*Delosperma cooperi* (Hook. f.) L. Bolus 'Jewel of Desert Ruby'], showy stonecrop (*Sedum lineare* Thunb. 'Autumn Fire'), and verbena (*Verbena canadensis* L. 'Homestead Purple') grown in 12.7-cm containers filled with soilless peat-based substrate and drenched with 90-mL aliquots of a solution containing 0, 125, 250, 500, 750, or 1000 mg·L$^{-1}$ ethephon at 10 d after transplant. Photographs were taken 3, 6, and 5 weeks after drench for iceplant, showy stonecrop, and verbena, respectively.

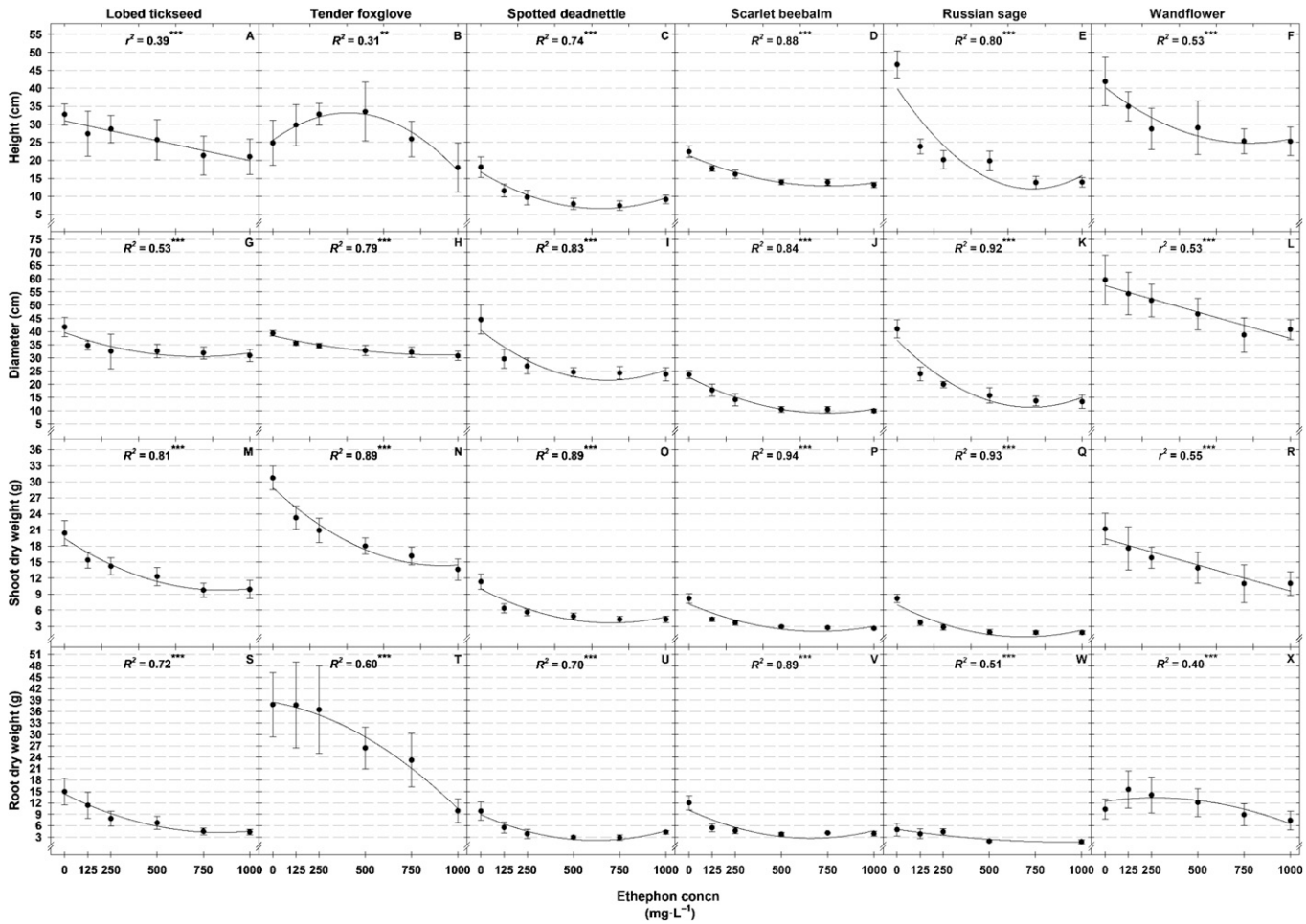


Fig. 7. Linear and quadratic regression for plant height (**A–F**), plant diameter (**G–L**), shoot dry weight (**M–R**), and root dry weight (**S–X**) of lobed tickseed (*Coreopsis auriculata* L. 'Leading Lady Iron'), tender foxglove (*Digiplexis* ×*hybrida* 'Berry Canary'), spotted deadnettle (*Lamium maculatum* L. 'Purple Dragon'), scarlet beebalm (*Monarda didyma* L. 'Pocahontas Red'), Russian sage (*Salvia yangii* B.T. Drew), and wandflower [*Oenothera lindheimeri* (Engelm. & A. Gray) W.L. Wagner & Hoch 'Siskiyou Pink'] grown in 16.5-cm containers filled with soilless peat-based substrate. Plants were drenched with 296-mL aliquots of a solution containing 0, 125, 250, 500, 750, or 1000 mg·L$^{-1}$ ethephon at 10 d after transplant and grown for 3 to 8 weeks after drench. Each symbol represents a mean of eight individual plant samples ($n = 8$), and error bars represent ±*SE*. For each model, corresponding $r^2$ (linear) or $R^2$ (quadratic) values and significance at $P \leq 0.001$ (**) or 0.0001 (***) are presented.

visible pollen) were recorded, and the percentage of plants flowering at termination was calculated for each species and ethephon drench concentration. After measurements were taken, shoots were excised at the substrate surface and all possible substrate was removed from roots while doing minimal damage to the root system with gentle washing in tap water. Shoots and roots were individually bagged and dried separately in a forced-air convection oven (179 L Fisherbrand™ Isotemp™ General Purpose Heating and Drying Oven; Fisher Scientific, Pittsburgh, PA, USA) at 65 °C. After 1 week, shoots and roots were weighed using an analytical balance (ME204E; Mettler Toledo, Columbus, OH, USA) to determine SDW and RDW, respectively.

*Experimental design and data analysis.* The experiment was conducted in a completely randomized design with eight single-plant replicates per species for each ethephon concentration. For each species, effects of ethephon concentration were analyzed with the general linear model (PROC GLM) for analysis of variance using SAS (version 9.4; SAS Institute, Cary, NC, USA). For flowering percentage, plant height, plant diameter, SDW, and RDW, regression analysis within species with ethephon concentration as the independent variable were performed using SAS regression procedure (PROC REG). Regression equations for plant height, plant diameter, SDW, and RDW for each species are listed in Table 3. For all analyses, a $P \leq 0.05$ was used to determine significant effects.

## Results

Increasing ethephon drench concentrations significantly influenced plant growth and development, including flowering precent, plant height, plant diameter, SDW, and RDW for most species investigated (Figs. 1–9). The magnitude of growth control achieved by increasing ethephon substrate drench concentrations varied among species, but the general trend of ethephon drenches resulting in smaller plants (height, diameter, and dry weights) was consistent across nearly all taxa. In addition, growth responses to ethephon substrate drenches exhibited a dose-dependent relationship, with higher concentrations typically resulting in more compact plant size.

Flowering percent decreased in some species as concentrations of ethephon increased (Table 4). For example, the percentage of pincushion flower and woodland sage flowering at the time of termination was significantly less when plants were treated with 250 or 500 mg·L$^{-1}$ ethephon, respectively, compared with untreated plants. For scarlet beebalm, Russian sage, wandflower, and blanket flower, diminished flowering was observed across all ethephon concentrations. Flowering of lobed tickseed, spotted deadnettle, Shasta daisy, wallflower, evening primrose, iceplant, showy stonecrop, and verbena was unaffected at any concentration of ethephon trialed.

Plant height was generally shorter in nearly all species with increasing concentrations of ethephon [Figs. 7A–F (Expt. 1), 8A–E (Expt. 2), and 9A–F (Expt. 3)]. For instance, compared with untreated plants, 125 and 250 mg·L$^{-1}$ ethephon controlled plant height of Russian

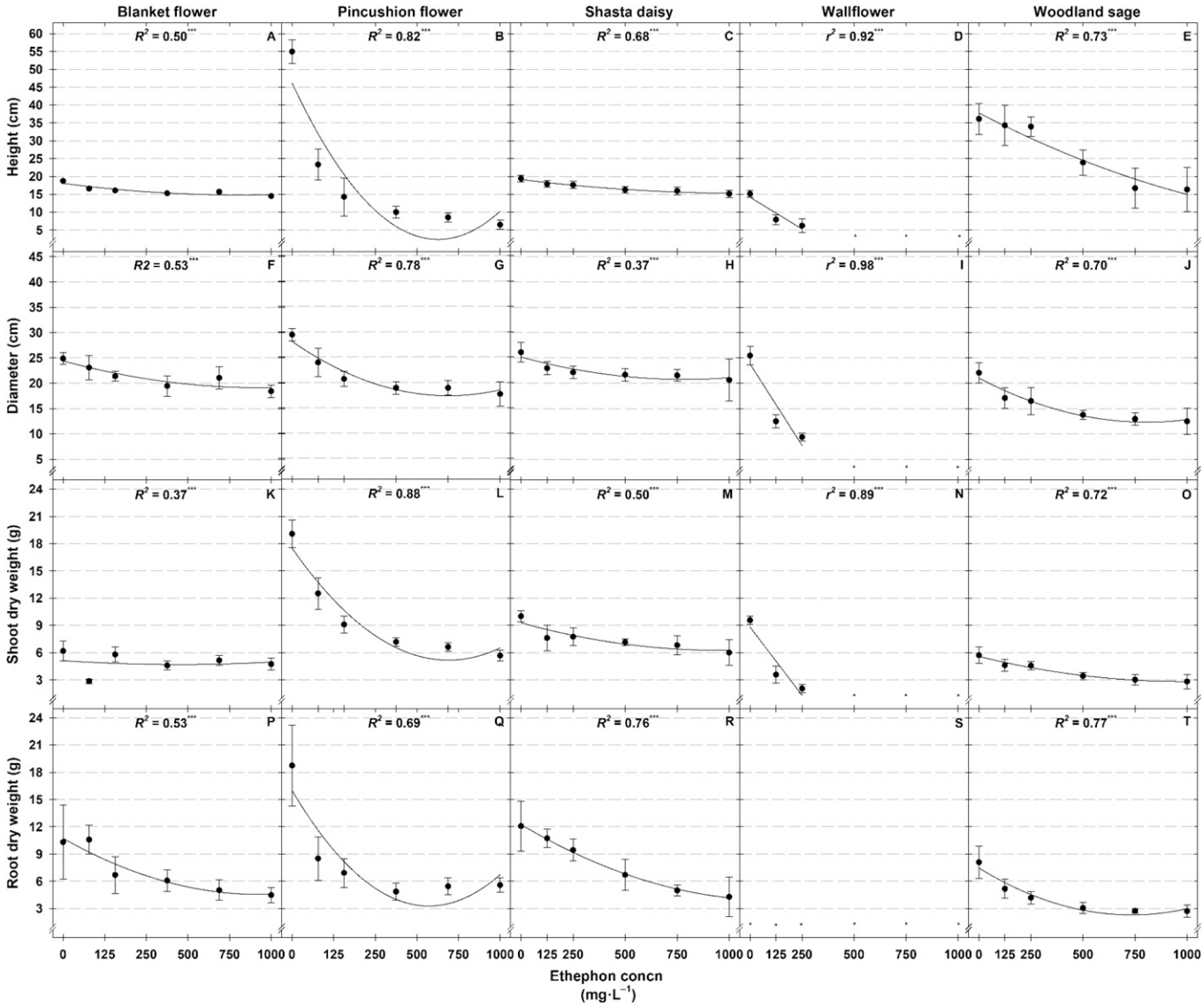


Fig. 8. Linear and quadratic regression for plant height (**A–E**), plant diameter (**F–J**), shoot dry weight (**K–O**), and root dry weight (**P–T**) of blanket flower (*Gaillardia aristata* Pursh. 'SpinTop® Red Starburst'), pincushion flower (*Scabiosa columbaria* L. 'Pink Mist'), Shasta daisy [*Leucanthemum maximum* (Ramond) DC. 'Snow Cap'], wallflower (*Erysimum ×hybrida* 'WallArt Citric'), and woodland sage (*Salvia nemorosa* L. 'East Friesland') grown in 16.5-cm containers filled with soilless peat-based substrate. Plants were drenched with 296 mL aliquots of a solution containing 0, 125, 250, 500, 750, or 1000 mg·L$^{-1}$ ethephon at 10 d after transplant and grown for 3 to 8 weeks after drench. An asterisk (*) indicates missing data due to plant death. Each symbol represents a mean of eight individual plant samples ($n = 8$), and error bars represent ±*SE*. For each model, corresponding $r^2$ (linear) or $R^2$ (quadratic) values and significance at $P \leq 0.0001$ (***) are presented.

sage (Fig. 7E), wandflower (Fig. 7F), and blanket flower (Fig. 8A) by 48% to 56% (22.7 to 26.4 cm), 16% to 31% (6.9 to 13.2 cm), and 11% to 14% (2.1 to 2.6 cm), respectively, and no further height control occurred when concentrations >250 mg·L$^{-1}$ ethephon were applied. Applying drenches containing 125 to 500 mg·L$^{-1}$ ethephon suppressed plant height of spotted deadnettle (Fig. 7C), scarlet beebalm (Fig. 7D), pincushion flower (Fig. 8B), Shasta daisy (Fig. 8C), and showy stonecrop (Fig. 9E) by 36% to 56% (6.6 to 10.2 cm), 21% to 37% (4.7 to 8.5 cm), 57% to 81% (31.6 to 44.9 cm), 8% to 16% (1.5 to 3.2 cm), and 11% to 34% (2.4 to 7.3 cm), respectively, compared with untreated plants. Evening primrose (Fig. 9B) and garden phlox (Fig. 9C) were significantly affected by higher concentrations of ethephon, and plant height was shorter by 48% (10.7 cm) and 64% (15.9 cm), respectively, when plants were drenched with 1000 mg·L$^{-1}$ ethephon compared with untreated plants. Plant height of ice plant (Fig. 9D) and verbena (Fig. 9F) was unaffected by any ethephon concentration trialed.

Plant diameter [Figs. 7G–L (Expt. 1), 8F–J (Expt. 2), and 9G–L (Expt. 3)] of most species was smaller by increasing concentrations of ethephon. For example, wallflower, (Fig. 8I), garden phlox (Fig. 9I), and showy stonecrop (Fig. 9K) drenched with 125 and 250 mg·L$^{-1}$ ethephon were 51% to 63% (12.9 to 16.1 cm), 23% to 38% (3.9 to 6.5 cm), and 29% to 37% (6.4 to 8.2) smaller, respectively, compared with untreated plants. In some species, growth control occurred at higher ethephon concentrations. Tender foxglove (Fig. 7H), scarlet beebalm (Fig. 7J), Russian sage (Fig. 7K), blanket flower (Fig. 8F), pincushion flower (Fig. 8G), woodland sage (Fig. 8J), catmint (Fig. 9G), and evening primrose (Fig. 9H) were narrower when plants were drenched with 500 mg·L$^{-1}$ ethephon. For example, as substrate drench concentrations increased from 0 to 500 mg·L$^{-1}$ ethephon, plant diameter of tender foxglove and blanket flower were 16% (6.5 cm) and 21% (5.4 cm) smaller, respectively. Furthermore, when drenched with 125 to 500 mg·L$^{-1}$ ethephon, catmint and evening primrose were 38% to 57% (13.8 to 20.8 cm) and 20% to 33% (5.0 to 8.1 cm) smaller, respectively, compared with untreated plants. Plant diameter of iceplant (Fig. 9J) was unaffected by ethephon drenches.

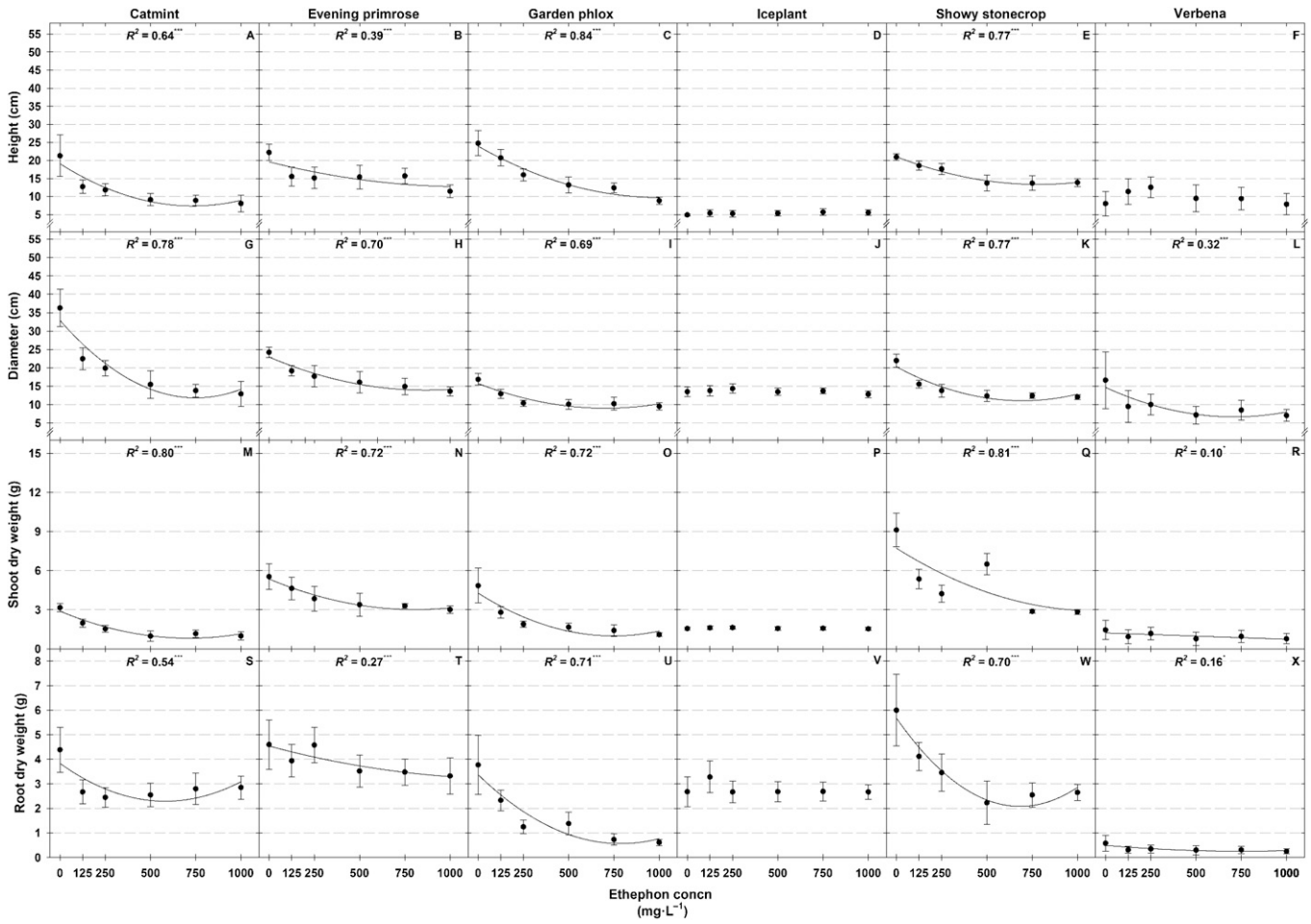


Fig. 9. Linear and quadratic regression for plant height (**A–F**), plant diameter (**G–L**), shoot dry weight (**M–R**), and root dry weight (**S–X**) of catmint (*Nepeta faassenii* E. Morren & Decne. 'Walkers Low'), evening primrose (*Oenothera speciosa* Sims. 'Twilight'), garden phlox (*Phlox paniculata* L. 'Flame Red'), iceplant [*Delosperma cooperi* (Hook. f.) L. Bolus 'Jewel of Desert Ruby'], showy stonecrop (*Sedum lineare* Thunb. 'Autumn Fire'), and verbena (*Verbena canadensis* L. 'Homestead Purple') grown in 12.7-cm containers filled with soilless peat-based substrate. Plants were drenched with 90-mL aliquots of a solution containing 0, 125, 250, 500, 750, or 1000 mg·L$^{-1}$ ethephon at 10 d after transplant and grown for 3 to 8 weeks after drench. Each symbol represents a mean of eight individual plant samples ($n = 8$), and error bars represent ±*SE*. For each model, corresponding $R^2$ (quadratic) values and significance at $P \leq 0.05$ (*) or 0.0001 (***) are presented.

SDW [Figs. 7M–R (Expt. 1), 8K–O (Expt. 2), and 9M–R (Expt. 3)] were less with increasing concentrations of ethephon, but the magnitude of growth control varied among species. Wallflower (Fig. 8N), evening primrose (Fig. 9N), and garden phlox (Fig. 9O) drenched with 250 mg·L$^{-1}$ ethephon were 78% (7.5 g), 38% (2.2 g), and 61% (2.9 g) smaller, respectively, than untreated plants. However, for most species evaluated, the maximum level of control observed in SDW was determined to be 500 mg·L$^{-1}$ ethephon. This includes lobed tickseed (Fig. 7M), spotted deadnettle (Fig. 7O), scarlet beebalm (Fig. 7P), Russian sage (Fig. 7Q), wandflower (Fig. 7R), pincushion flower (Fig. 8L), Shasta daisy (Fig. 8M), woodland sage (Fig. 8O), catmint (Fig. 9M), and showy stonecrop (Fig. 9Q). For example, lobed tickseed, Russian sage, and Shasta daisy drenched with 125 to 500 mg·L$^{-1}$ ethephon were 24% to 39% (5.0 to 8.1 g), 54% to 76% (4.5 to 6.3 g), and 23% to 28% (2.4 to 2.8 g) smaller, respectively, compared with untreated plants. Concentrations above 500 mg·L$^{-1}$ ethephon did not yield additional levels of control in these species. SDW of ice plant (Fig. 9D) and verbena (Fig. 9F) was unaffected at all trialed concentrations of ethephon.

RDW generally diminished with increasing substrate drench concentrations of ethephon, with the level of reduction varying between species [Figs. 7S–10 (Expt. 1), 8P–T (Expt. 2), and 9S–X (Expt. 3)]. Spotted deadnettle (Fig. 7U), scarlet beebalm (Fig. 7V), blanket flower (Fig. 8P), pincushion flower (Fig. 8Q), garden phlox (Fig. 9U), and showy stonecrop (Fig. 9W) drenched with 250 mg·L$^{-1}$ ethephon resulted in significantly lower RDW than untreated control plants. For instance, when drenched with 250 mg·L$^{-1}$ ethephon, blanket flower and garden phlox RDW were 42% (4.5 g) and 66% (2.5 g) lower, respectively, compared with untreated plants. In other species such as lobed tickseed (Fig. 7S), Russian sage (Fig. 7W), Shasta daisy (Fig. 8R), and woodland sage (Fig. 8T), RDW diminished by 54% (8.2 g), 61% (3.0 g), 44% (5.4 g), and 65% (5.8 g), respectively, when drenched with 500 mg·L$^{-1}$ ethephon compared with the untreated plants. RDW of iceplant (Fig. 9V) was unaffected by increasing ethephon concentrations.

## Discussion

We found ethephon substrate drenches controlled plant height in most of the species trialed, although the magnitude of growth control varied across species. Our results agree with previous research investigating ethephon substrate drenches on annual bedding plants and herbaceous perennials (Aiken et al. 2015; Currey et al. 2016; Miller et al. 2012). Miller et al. (2012) found reduced stem length in 23 species of annual bedding plants. For example, when drenched with 200 mg·L$^{-1}$ ethephon, stem length of 'Serena Lavander' angelonia (*Angelonia angustifolia* Benth.), 'Cooler Grape' Madagascar periwinkle [*Catharanthus roseus* (L.) G. Don.], and 'New Look' plume cockscomb (*Celosia argentea* L. var. *plumosa* Voss.) were 53%, 59%, and 70% less, respectively (Miller et al. 2012). Furthermore, the authors found that

Table 4. Flowering percentages of 17 herbaceous perennials {Expt. 1: lobed tickseed (*Coreopsis auriculata* L. 'Leading Lady Iron'), tender foxglove (*Digiplexis ×hybrida* 'Berry Canary'), spotted deadnettle (*Lamium maculatum* L. 'Purple Dragon'), scarlet beebalm (*Monarda didyma* L. 'Pocahontas Red'), Russian sage (*Salvia yangii* B.T. Drew), and wandflower [*Oenothera lindheimeri* (Engelm. & A. Gray) W.L. Wagner & Hoch 'Siskiyou Pink']; Expt. 2: blanket flower (*Gaillardia aristata* Pursh. 'SpinTop® Red Starburst'), pincushion flower (*Scabiosa columbaria* L. 'Pink Mist'), Shasta daisy [*Leucanthemum maximum* (Ramond) DC. 'Snow Cap'], wallflower (*Erysimum ×hybrida* 'WallArt Citric'), and woodland sage (*Salvia nemorosa* L. 'East Friesland'); and Expt. 3: catmint (*Nepeta faassenii* E. Morren & Decne. 'Walkers Low'), evening primrose (*Oenothera speciosa* Nutt. 'Twilight'), garden phlox (*Phlox paniculata* L. 'Flame Red'), iceplant [*Delosperma cooperi* (Hook. f.) L. Bolus 'Jewel of Desert Ruby'], showy stonecrop (*Sedum lineare* Thunb. 'Autumn Fire'), and verbena (*Verbena canadensis* L. 'Homestead Purple')} drenched with 0, 125, 250, 500, 750, or 1000 mg·L$^{-1}$ ethephon at 10 d after transplant and grown for 3 to 8 weeks after drench. Percentages were determined at termination. Plants were transplanted into 12.7-cm (946 mL) or 16.5-cm (1.7 L) containers filled with a peat-based substrate and grown in a glass-glazed greenhouse under ambient daylight supplemented with ≈120 µmol·m$^{-2}$·s$^{-1}$ from 1000-W light-emitting diode lamps from 0600 to 2200 HR (16-h photoperiod) to maintain a DLI of 10 to 14 mol·m$^{-2}$·d$^{-1}$. Canopy air temperature setpoint was 20 °C.

| | Ethephon concn (mg·L$^{-1}$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Herbaceous perennials | 0 | 125 | 250 | 500 | 750 | 1000 | Significance[i] | Regression ($R^2$)[ii] |
| Expt. 1 | | | | | | | | |
| Lobed tickseed | 50 | 25 | 13 | 25 | 0 | 0 | NS | NS[iii] |
| Tender foxglove | 63 a[iv] | 25 ab | 25 ab | 0 b | 0 b | 0 b | L*** Q*** | 0.30 |
| Spotted deadnettle | 25 | 0 | 0 | 0 | 0 | 0 | NS | NS |
| Scarlet beebalm | 38 a | 0 b | 0 b | 0 b | 0 b | 0 b | L$^{NS}$ Q** | 0.20 |
| Russian sage | 50 a | 0 b | 0 b | 0 b | 0 b | 0 b | L*** Q*** | 0.28 |
| Wandflower | 63 a | 0 b | 0 b | 0 b | 0 b | 0 b | L** Q*** | 0.36 |
| Expt. 2 | | | | | | | | |
| Blanket flower | 25 a | 88 b | 88 b | 88 b | 100 b | 100 b | L*** Q*** | 0.30 |
| Pincushion flower | 100 a | 75 a | 0 b | 0 b | 0 b | 0 b | L** Q*** | 0.34 |
| Shasta daisy | 50 | 63 | 50 | 100 | 75 | 75 | NS | NS |
| Wallflower | 25 | 25 | 0 | —[v] | — | — | NS | NS |
| Woodland sage | 88 a | 88 a | 100 a | 13 b | 0 b | 0 b | L*** Q*** | 0.64 |
| Expt. 3 | | | | | | | | |
| Catmint | 63 a | 13 b | 0 b | 0 b | 0 b | 0 b | L*** Q*** | 0.36 |
| Evening primrose | 25 | 0 | 0 | 0 | 0 | 0 b | NS | NS |
| Garden phlox | 38 ab | 50 ab | 63 a | 25 ab | 0 b | 0 b | L** Q*** | 0.20 |
| Iceplant | 100 | 100 | 100 | 100 | 100 | 100 | NS | NS |
| Showy stonecrop | 0 | 0 | 0 | 0 | 0 | 0 | NS | NS |
| Verbena | 25 | 25 | 50 | 13 | 13 | 13 | NS | NS |

[i] Linear (L) or quadratic (Q) response for ethephon substrate drench concentration. Significance at $P \leq 0.01$ (**) or 0.001 (***) or nonsignificant (NS).
[ii] Corresponding $R^2$ (quadratic) are presented for each species.
[iii] Nonsignificant (NS).
[iv] Within-row means (n = 8) followed by different lower-case letters are significantly different by Tukey's honestly significant difference test at $P \leq 0.05$.
[v] No data recorded.

'Angel Mist White Cloud' angelonia, 'Cabaret Pink Hot' calibrachoa (*Calibrachoa ×hybrida* Cerv. hybrid), and 'Aromatica Royal' nemesia [*Nemesia fruticans* (Thunb.) Benth.] treated with 200 mg·L$^{-1}$ ethephon were 8.9, 8.3, and 11.6 cm shorter, respectively, than untreated plants (Miller et al. 2012). Even though Miller et al. (2012) drenched plants with lower ethephon concentrations than in our study, we obtained a similar trend of greater plant height control as ethephon substrate drench concentration increased. This is consistent with Aiken et al. (2015) who reported significant control in plant height of 'Lollipop' verbena (*Verbena bonariensis* L.) drenched with 100 mg·L$^{-1}$ ethephon, compared with untreated plants. Currey et al. (2016) also found 'Serena White' angelonia drenched with 100 mg·L$^{-1}$ ethephon and 'Pinto Premium Deep Red' geranium (*Pelargonium ×hortorum* L.H. Bailey) drenched with 200 mg·L$^{-1}$ ethephon were 18% (5.4 cm) and 32% (9.5 cm) shorter, respectively, than untreated plants when treated 10 d after transplant. Our research along with research by Miller et al. (2012) and Currey et al. (2016) contrast findings from Barker et al. (2016) who found no significant differences in plant height of 'Imperial Dark Blue' plumbago (*Plumbago auriculata* Lam.) drenched with 125, 250, 500, or 1000 mg·L$^{-1}$ ethephon. Overall, our research demonstrates that 250 to 750 mg·L$^{-1}$ ethephon can effectively control plant height in most herbaceous perennial species trialed.

In addition to plant height, plant diameter was also significantly affected by increasing concentrations of ethephon. Our results are consistent with Barker et al. (2016) who reported a 38% reduction in plant diameter of 'Imperial Dark Blue' plumbago when drenched with 1000 mg·L$^{-1}$ ethephon, compared with untreated plants. Similarly, Currey et al. (2016) found plant diameter of 'Serena White' angelonia to be 38% (10.2 cm) smaller as substrate drench concentrations increased from 0 to 100 mg·L$^{-1}$ ethephon. Our results compliment both studies, and we suggest that 125 to 500 mg·L$^{-1}$ ethephon provides adequate plant diameter growth control in most of the species trialed.

Reductions in SDW were observed with increasing concentrations of ethephon. Our results support findings by Miller et al. (2012) who found a reduction in SDW of 16 bedding plant species. For example, as substrate drench concentration increased from 0 to 200 mg·L$^{-1}$ ethephon, SDW decreased by 76% and 36% for 'New Look' plume cockscomb and lobelia (*Lobelia erinus*), respectively (Miller et al. 2012). Comparably, Currey et al. (2016) found that 'Serena White' angelonia drenched 10 d after transplant with 100 mg·L$^{-1}$ ethephon was 34% (1.7 g) smaller than untreated plants. Our research along with these previous studies demonstrate that ethephon substrate drenches can effectively control SDW. Furthermore, our research concludes substrate drenches of 250 to 500 mg·L$^{-1}$ ethephon provides the greatest level of control in SDW, for most species trialed.

RDW of most species trialed herein were influenced by increasing concentrations of ethephon, although to different magnitudes. For many of the species, substrate drenches of 125 to 500 mg·L$^{-1}$ ethephon significantly suppressed root growth, and thus RDW, compared with untreated plants. Our observations are consistent with Miller et al. (2012) who reported RDW of 'Madeira Cherry Red' marguerite daisy [*Argyranthemum frutescens* (L.) Sch. Bip.], 'Cabaret Pink Hot' calibrachoa, 'Wink Coral' diascia (*Diascia barberae* Hook. F.), 'Aromatica Royal' nemesia, 'Zion Orange' African daisy [*Osteospermum ecklonis* (DC.) Norl.], 'Abunda Giant White' bacopa (*Sutera cordata* Roth.), 'Crested Janie Deep Orange' French marigold (*Tagetes patula* L.), and 'Penny Lane Mixed' viola (*Viola cornuta* L.) to decrease with increasing ethephon drench concentrations. For instance, RDW of 'Aromatica Royal' nemesia drenched with 200 mg·L$^{-1}$ ethephon were 38% (1.97 g) smaller than untreated plants. In addition, Currey et al. (2016) found RDW of 'Serena White' angelonia and 'Pinto Premium Deep Red' geranium drenched with 200 mg·L$^{-1}$ to be 54% (0.51 g) and 11%

Table 5. Suggested ethephon substrate drench trialing concentrations of 17 herbaceous perennials {Expt. 1: lobed tickseed (*Coreopsis auriculata* L. 'Leading Lady Iron'), tender foxglove (*Digiplexis ×hybrida* 'Berry Canary'), spotted deadnettle (*Lamium maculatum* L. 'Purple Dragon'), scarlet beebalm (*Monarda didyma* L. 'Pocahontas Red'), Russian sage (*Salvia yangii* B.T. Drew), and wandflower [*Oenothera lindheimeri* (Engelm. & A. Gray) W.L. Wagner & Hoch 'Siskiyou Pink']; Expt. 2: blanket flower (*Gaillardia aristata* Pursh. 'SpinTop® Red Starburst'), pincushion flower (*Scabiosa columbaria* L. 'Pink Mist'), Shasta daisy [*Leucanthemum maximum* (Ramond) DC. 'Snow Cap'], wallflower (*Erysimum ×hybrida* 'WallArt Citric'), and woodland sage (*Salvia nemorosa* L. 'East Friesland'); and Expt. 3: catmint (*Nepeta faassenii* E. Morren & Decne. 'Walkers Low'), evening primrose (*Oenothera speciosa* Nutt. 'Twilight'), garden phlox (*Phlox paniculata* L. 'Flame Red'), iceplant [*Delosperma cooperi* (Hook. f.) L. Bolus 'Jewel of Desert Ruby'], showy stonecrop (*Sedum lineare* Thunb. 'Autumn Fire'), and verbena (*Verbena canadensis* L. 'Homestead Purple')}. Plants were transplanted into 12.7-cm (946 mL) or 16.5-cm (1.7 L) containers filled with a peat-based substrate and grown in a glass-glazed greenhouse under ambient daylight supplemented with ≈120 $\mu mol \cdot m^{-2} \cdot s^{-1}$ from 1000-W light-emitting diode lamps from 0600 to 2200 HR (16-h photoperiod) to maintain a DLI of 10 to 14 $mol \cdot m^{-2} \cdot d^{-1}$. Canopy air temperature setpoint was 20 °C.

| Botanical name | Common name | Cultivar | Ethephon drench concentrations ($mg \cdot L^{-1}$) | Effects |
|---|---|---|---|---|
| *Coreopsis auriculata* | Lobed tickseed | Leading Lady Iron | 125–750 | Controlled plant height and diameter. No significant delay in flowering was observed, but lower leaf chlorosis was observed at $>750$ $mg \cdot L^{-1}$ ethephon. |
| *Delosperma cooperi* | Iceplant | Jewel of Desert Ruby | ≥1000 | Provided no growth control. No delay in flowering or growth control was observed at any ethephon substrate drench concentrations trialed. |
| *Digiplexis ×hybrida* | Tender foxglove | Berry Canary | 125–750 | Controlled plant height and plant diameter. A delay in flowering was observed in plants drenched with ≥ 500 $mg \cdot L^{-1}$ ethephon. |
| *Erysimum ×hybrida* | Wallflower | WallArt Citric | 125–250 | Controlled plant height and plant diameter. Leaf reddening was observed in plants drenched with 250 $mg \cdot L^{-1}$ ethephon. Plant death occurred at ≥ 500 $mg \cdot L^{-1}$ ethephon. |
| *Gaillardia aristate* | Blanket flower | SpinTop® Red Starburst | 250–500 | Controlled plant height and plant diameter. Lower leaf chlorosis was observed in plants drenched with ≥ 1000 $mg \cdot L^{-1}$ ethephon. No delay in flowering was observed. |
| *Lamium maculatum* | Spotted deadnettle | Purple Dragon | 125–250 | Controlled plant height and plant diameter. Leaf purpling, leaf necrosis, and death of lateral meristems was observed at ≥ 250 $mg \cdot L^{-1}$ ethephon. No delay in flowering was observed. |
| *Leucanthemum maximum* | Shasta daisy | Snow Cap | 125–500 | Controlled plant height and plant diameter. Lower leaf chlorosis was observed in plants drenched with 1000 $mg \cdot L^{-1}$ ethephon. |
| *Monarda didyma* | Scarlet beebalm | Pocahontas Red | 125–250 | Controlled plant height and plant diameter. Leaf epinasty was observed at all trialed concentrations and leaf chlorosis and necrosis was observed at ≥ 500 $mg \cdot L^{-1}$ ethephon. A delay in flowering was observed in plants drenched at all ethephon concentrations. |
| *Nepeta faassenii* | Catmint | Walkers Low | 125–500 | Controlled plant height and plant diameter. Phytotoxic effects including leaf epinasty, leaf chlorosis, and meristem necrosis were observed at ≥ 500 $mg \cdot L^{-1}$ ethephon. |
| *Oenothera lindheimeri* | Wandflower | Siskiyou Pink | 125–500 | Controlled plant height and plant diameter. A delay in flowering was observed in plants drenched at all ethephon concentrations. |
| *Oenothera speciosa* | Evening primrose | Twilight | 250–750 | Controlled plant height and plant diameter. No delay in flowering was observed. |
| *Phlox paniculata* | Garden phlox | Flame Red | 125–500 | Controlled plant height and plant diameter. Leaf chlorosis was observed at ≥ 500 $mg \cdot L^{-1}$ ethephon. A delay in flowering was observed at ≥ 750 $mg \cdot L^{-1}$ ethephon. |
| *Salvia nemorosa* | Woodland sage | East Friesland | 125–500 | Controlled plant height and plant diameter. A delay in flowering was observed in plants drenched with ≥ 500 $mg \cdot L^{-1}$ ethephon. |
| *Salvia yangii* | Russian sage | | 125–500 | Controlled plant height and plant diameter. Severe stunting was exhibited in plants drenched with ≥ 500 $mg \cdot L^{-1}$ ethephon. A delay in flowering was observed in plants drenched at all ethephon concentrations. |
| *Scabiosa columbaria* | Pincushion flower | Pink Mist | 125–500 | Controlled plant height and plant diameter. Leaf purpling and meristem death was observed at substrate drenches of ≥ 500 $mg \cdot L^{-1}$ ethephon. A delay in flowering was observed at ≥ 250 $mg \cdot L^{-1}$ ethephon. |
| *Sedum lineare* | Showy stonecrop | Autumn Fire | 125–500 | Controlled plant height and plant diameter. Leaf cupping was observed in plants drenched with ≥ 125 $mg \cdot L^{-1}$ ethephon. |
| *Verbena canadensis* | Verbena | Homestead Purple | 125–1000 | Controlled plant diameter. No significant delay in flowering was observed. |

(0.09 g) smaller than untreated plants. Reductions of RDW in our study were expected because ethylene is known to impact root development. Khoury et al. (2024) report that exogenous applications of ethylene gas or its precursor, aminocyclopropane-1-caboxylic acid (ACC), begin inhibiting root elongation 5 min after application and limited root branching and the development of root hairs in *Arabidopsis*. As such, it is speculated that ethephon substrate drenches impact the development and expansion of the root system leading to reduced RDW and subsequently limiting plant growth and biomass accumulation in addition to the effects of ethephon translocated to the shoot inhibiting cell elongation.

We found two herbaceous perennial species to be unaffected by ethephon substrate drenches. Plant height, plant diameter, SDW, and RDW of iceplant and plant height and SDW of verbena were unaffected at each ethephon concentration trialed. These responses are not unexpected because Miller et al. (2012) reported height of 'Wink Coral' diascia, 'Beefmaster' tomato (*Lycopersicon esculentum* L.), 'Zion Orange' African daisy, and 'Dreams Burgundy' petunia (*Petunia ×grandiflora*) was unaffected when plants were drenched with 25, 50, 100, or 200 $mg \cdot L^{-1}$ ethephon. Furthermore, Miller et al. (2012) suggested that taxa, application timing, temperature, light, substrate composition, and other environmental factors could influence ethephon drench efficacy. We speculate the lack of response of iceplant and verbena to ethephon substrate drenches at increasing concentrations is attributed to a lack of sensitivity to ethylene, as we controlled the greenhouse environment (light and temperature), applied

ethephon in the morning when plants were not stressed, and grew plants in peat-based substrates like other studies. However, substrate pH is known to influence ethephon efficacy (Aiken et al. 2015) and ethephon is known to be an acidifier. We determined substrate pH before and after ethephon drench application and as expected, substrate pH dropped after drench application which may or may not have affected the ethephon efficacy and impending impact on plant growth. However, pH increased over the course of each experiment and 88% of the species trialed exhibited growth control, therefore, we attribute the lack of growth control observed in iceplant and verbena to be a result of an unknown exogenous or endogenous factor. Further research investigating other iceplant and verbena species and cultivars, higher drench concentrations, and environmental and root zone factors are warranted.

A slight delay in flowering was observed in a few perennial species trialed, but only at concentrations ≥500 mg·L$^{-1}$ ethephon (Table 4). It is important to note that even though lobed tickseed treated with higher ethephon concentrations did not display open flowers or anthesis, all plants, regardless of drench concentration, developed visible flower buds at time of termination. In iceplant, flowering was unaffected regardless of ethephon drench concentration as all plants were flowering at termination. As such, since time to flower varied widely among species in the current study, in-house grower trials are recommended to determine if a significant delay in flowering will occur and disrupt production schedules.

Some phytotoxic effects were observed at high concentrations of ethephon. In some species, leaf epinasty, lower leaf chlorosis, and necrosis of the leaf margins were observed and are reported in Table 5. For example, in scarlet beebalm (Fig. 2), epinasty manifested and leaves became rigid with a downward orientation at each ethephon concentration trialed, and over time, meristems progressed from active growth to complete necrosis when treated with ≥500 mg·L$^{-1}$ ethephon. However, death of the meristem is not unexpected in some species as ethephon is known to increase lateral branching by reducing apical dominance and facilitating the growth of axillary buds (Currey 2018). Furthermore, at 1000 mg·L$^{-1}$ ethephon, lower leaf chlorosis and leaf epinasty were observed in Shasta daisy (Fig. 3) and catmint (Fig. 5), respectively. Due to these effects, it is suggested container herbaceous perennial producers perform in-house trials to ensure the desired growth control effects are achieved, and phytotoxic effects do not develop and cause damage to ornamental aesthetic quality and value.

## Conclusions

This research has expanded the use of ethephon and found substrate drenches to be an effective and promising application method to control growth of containerized herbaceous perennials. As some species were unresponsive to ethephon drenches and others experienced extreme phytotoxic effects, further research defining the sensitivity of herbaceous perennials to ethephon substrate drenches is needed. Herbaceous perennial growers should consider performing in-house trials to determine taxa-specific ethephon concentrations of species and cultivars not investigated herein or to evaluate our suggestions based on their crop culture procedures, growing environment, and market demands, though we suggest 125 to 500 mg·L$^{-1}$ ethephon as an initial range for trials.

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