Perennial Flax: A Potential Cut Flower Crop

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Abstract. The genus *Linum* L. contains ≈200 primarily blue-flowered species, including several ornamentals, yet no reports exist regarding the cut flower potential of this genus. The objective of this study was to evaluate the cut flower potential of perennial flax cultivars (*L. perenne* L. ‘Blue Flax’ and ‘Sapphire’; Expt. 1, 2018) and accessions (*L. austriacum* L., *L. lewisii* Pursh., and *L. perenne*; Expt. 2, 2019), and record traits that will enable breeding and selection for improved cut flower performance. The mean vase life across both cultivars in Expt. 1 was 9.2 days. In Expt. 2, *L. perenne* had the longest average vase life (9.3 days), followed by *L. austriacum* (9.1 days) and *L. lewisii* (8.3 days). The floral preservative (Floralife 300) significantly increased vase life by an average of 1.7 days in Expt. 1, and 1.6 days in Expt. 2, and resulted in a significantly greater number of flowers (≈2x) in both experiments. Significant variation was observed among genotypes for most traits, including vase life (6.2 to 11.3 days) and number of flowers (1.3 to 10.5), highlighting the opportunities for improving the potential of cut flower perennial flax through breeding.

The genus *Linum* contains ≈180 to 200 species (Bolsheva et al., 2017; McDill et al., 2009). The most well-known of these is domesticated annual flax, *L. usitatissimum* L., common flax or linseed. Originally domesticated in the Fertile Crescent, this species has been cultivated since ≈8000 B.C.E, making it one of the earliest domesticated plants (McDill et al., 2009; Vaisey-Genser and Morris, 2003). Throughout history, flax has been highly valued as a multiuse crop for fiber, feed, and industrial applications (Vaisey-Genser and Morris, 2003).

Linum also contains a large number of wild perennial species that are distributed throughout the temperate and subtropical regions of Europe, Asia, and North America (Bolsheva et al., 2017; McDill et al., 2009). Several species of *Linum* have a history of cultivation as ornamentals, including *L. perenne* L., *L. austriacum* L., *L. narbonense* L.,

L. grandiflorum Desf., and *L. flavum* L., although few reports are available on the variation available for ornamental breeding, including for cut flower uses (Cullis, 2011; Diederichsen and Richards, 2003; Fu, 2019). Initial surveys of *Linum* have identified *L. austriacum*, *L. lewisii* Pursh, and *L. perenne* as the top perennial species of interest for ornamental flax breeding at the University of Minnesota (Betts et al., 2008). The native status and self compatibility of *L. lewisii* make it a favorable candidate for breeding (Ruiz-Martin et al., 2018), although it lacks vigor in Minnesota compared with the naturalized, self-incompatible European species *L. perenne* and *L. austriacum* [D. Tork, unpublished data; U.S. Department of Agriculture–National Resources Conservation Service (USDA-NRCS, 2021)].

An integral part of the cut flower industry is the introduction of new species and unique or rare flower colors that can drive consumer interest and increase sales (Dole et al., 2009). Flax possesses relatively small, but striking blue flowers, along with finely textured foliage, making it well suited as a filler material. In floral design, filler flowers are small flowers used to accent the larger, primary flowers by filling empty spaces and adding accents of complementary color or texture (Hunter, 2013). Perennial flax has the potential to become a new specialty cut flower for cold climates like Minnesota (Tork et al., 2019), but to the best of our knowledge, there are no existing reports on vase life performance of any *Linum* species.

Vase life studies typically involve harvesting flower stems from field- or greenhouse-grown plants. Immediately following harvest, stems are hydrated using unamended water or a commercial hydrator to maintain floral quality during short-term (<24 h) transport, after which they are placed in floral preservative, a long-term holding solution (Clark et al., 2010). Vase life experiments evaluate commercially relevant factors, such as the type of vase solution, harvest timing, storage conditions (wet, dry), and environmental conditions (temperature, light, humidity) (Fanourakis et al., 2013; Redman et al., 2002; Reid and Jiang, 2012; Skutnik et al., 2020). The goal of these evaluations is to extend vase life and improve postharvest floral development and quality. The results are then used to develop specific handling recommendations for cut flower growers, wholesalers, and florists to help drive demand and widespread adoption of the species or cultivar tested (Dole et al., 2009).

One of the most common factors evaluated in vase life studies is the vase solution. For example, the use of floral preservative, which is typically composed of sucrose (plant food), a pH adjuster (acid), and a biocide to reduce bacterial growth, often results in an extended vase life, greater postharvest bud opening, flower size, flower longevity, and improved color (Dole et al., 2009; Pun and Ichimura, 2003; Reid and Jiang, 2012). Response to vase solution treatments is often genotype- or species-specific, and can vary significantly, even among cultivars of similar ancestry (Clark et al., 2010; Janowska and Jerzy, 2004; Reid and Jiang, 2012).

The objective of this study was to characterize the effect of floral preservative on vase life and other commercially relevant traits for the *L. perenne* cultivars Sapphire and Blue Flax (Expt. 1), and USDA accessions of the species *L. austriacum*, *L. lewisii*, and *L. perenne* (Expt. 2). A secondary objective of Expt. 2 was to assess if any easily recorded stem phenotypes were correlated with postharvest traits, as this could facilitate more efficient breeding. Trait variation among genotypes and species is discussed in the context of breeding, which also provides expectations for the commercial use of perennial flax as a cut flower.

Materials and Methods

Expt. 1

Expt. 1, in year one (Y1; Fall 2018), tested two commercial *L. perenne* cultivars grown at University Research and Outreach Centers in Grand Rapids (lat. 47°14'50.604"N, long. 93°32'39.983"W), Morris (lat. 45°37'41.520"N, long. 95°53'20.688"W), and Waseca, MN (lat. 43°54'24.084"N, long. 93°26'0.167"W). Plug trays (72s) of ‘Sapphire’ and ‘Blue Flax’ rooted liners were obtained from The Nursery Stock Market, Inc. (Presswood, KY). Ten clones per cultivar were planted for each cultivar in spaced rows (45.2 cm on center within rows and 61.0 cm between rows) at each site in a completely randomized design (CRD). The Waseca site was

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later dropped from the experiment due to insufficient weed control. Thus, cut flowers from only two sites were tested.

Harvest. Harvest occurred in a single day at each site during week 37 (13 Sept. 2018) with the Grand Rapids, MN, site being harvested first (0800–1000 HR), followed by Morris, MN, later that day (1400–1600 HR). Flax produces clusters of flower buds that bloom sequentially, so the primary harvest criterion was that the stem possessed healthy unspent flower buds. Six to eight flowering stems per plant were harvested from both cultivars at both locations. Stem length was not measured.

Stems were cut at the base using hand clippers (Felco, Model 2; U.S. Felco subsidiary: Pygar USA, Inc. Seattle, WA), which were sterilized in ethanol (70% EtOH) between plants. Immediately after cutting, stems from the same plant were grouped and wrapped in a moist paper towel, then placed in a plastic bag (Ziploc Freezer Gallon; S. C. Johnson & Son, Inc., Racine, WI) to hold in moisture. Bags containing harvested stems were immediately placed on ice in a cooler for transport. The ice was covered with a towel before loading the samples into the cooler to prevent cold damage to the stems. After both sites were harvested, stems were transported immediately back to St. Paul, MN, for overnight storage in a 4°C walk-in cooler located at the Plant Growth Facilities, St. Paul Campus, University of Minnesota, St. Paul, MN (lat. 44°59'17.8"N, long. –93°10'51.6"W). All stems were in storage by 2130 HR on the harvest day.

Experimental design. Experimentation took place in the laboratory under 24-h light with an average intensity of 10.86 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ and an ambient air temperature of 21°C day/night. Two vase solutions were tested: a) deionized and distilled water (control), and b) a floral preservative solution (FloraLife Crystal Clear Flower Food 300; Florilife, Walterboro, SC) mixed according to recommendation (10 g·L⁻¹ water). Each vase was filled with 200 mL of either solution and arranged using a CRD with one stem per vase. Stems were stripped of the lower half of leaves and 2.5 cm (1 inch) was cut from the base of the stem using a sterilized scalpel blade to prevent debris from contaminating the stem solution. After cutting, each stem was immediately placed in the assigned vase to begin the experiment.

Expt. 2

Expt. 2, in year two (Y2; Fall 2019), compared accessions from three perennial species, *L. perenne*, *L. austriacum*, and *L. lewisii*, grown in a common garden nursery located at Rosemount Research and Outreach Center, Rosemount, MN (lat. 44°42'58.2"N, long. –93°5'54.9"W) with the same spacing within rows (45.7 cm O.C.) as Expt. 1 but with differing row spacing (1.5 m), determined by the cultivation equipment available at each site. Seeds were sown in 288-plug trays (Landmark Plastic, Akron, OH) in a peatmoss-based substrate (BM2 Seed Germination and Propa-

gation Mix; Berger, Saint-Modeste, QC, Canada) and covered with fine vermiculite (Palmetto Vermiculite Medium A-2; Palmetto Vermiculite, Woodruff, SC) in weeks 14 and 15 (5, 12 Apr. 2019). All plug trays were placed in a mist house for 4 h to moisten the soilless medium using an intermittent mist system (St. Paul, MN, Plant Growth Facility, University of Minnesota; lat. 44°59'17.8"N, long. –93°10'51.6"W) at a mist frequency of 10-min intervals (mist nozzles, reverse osmosis water) during 0600–2200 HR with a 7-s duration (21/21°C, day/night, 16 h; 0600–2200 HR) with lighting supplied by high-pressure sodium high-intensity discharge (HID) lamps at a minimum set point of 150 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. Once watered in, the trays were covered with plastic dome lids (Super Sprouter Standard Vented Humidity Dome 7 inches; Hawthorne Gardening Company, Vancouver, WA) and transferred to a walk-in cooler for 2 weeks at 4/4°C day/night in darkness to break seed dormancy (cold stratification), which is recommended for most wild *Linum* species (K. Betts, personal communication; Barbara Atkins, STA Laboratories, Longmont, CO). Trays were uncovered and misted by hand, as needed, over this 2-week period to maintain adequate moisture levels in the soilless medium. After the 2-week stratification, the dome lids were removed, and the trays were returned to the mist house for an additional 3 weeks. Plug trays were then moved onto capillary mats in a greenhouse at 16.7/15.5°C day/night daily integral and a 16-h photoperiod (0600–2200 HR; long days). Supplemental lighting was supplied during cloudy days by 400-W high-pressure sodium-HID (HPS-HID) lamps, at a minimum of 150 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ at plant level. Fertigation

(Mondays–Fridays) provided nutrients at a constant liquid feed rate of 125 mg N/L from 20N–0.44P–16.6K water-soluble fertilizer (Peters Professional 20–10–20 Peat-Lite Special, Summerville, SC). Accessions were placed in the greenhouse on weeks 19 and 20 (10, 17 May 2019) until transplanting in week 24 (13 June 2019). Accessions were randomized for planting, and 20 seedlings per genotype were transplanted. The field was irrigated post-planting with 2.5 cm water per week. Irrigation continued throughout the summer to maintain a minimum of 2.54 cm water per week when there was insufficient rainfall. Weed control consisted of weekly mechanical tillage between rows, preemergent herbicide applications (Fortress; OHP Inc., Bluffton, SC) at the recommended rates, and biweekly hand weeding within rows.

Selection of genotypes for testing. All accessions for Expt. 2 were obtained as seed from the USDA–Germplasm Resources Information Network (USDA-GRIN) and Plant Gene Resources of Canada (GRIN-CA). Before selecting genotypes for testing, individual plants were identified that met three criteria: 1) the plant had sufficient number of stems (six) in bloom, 2) stems were ≥ 30 cm in length, and 3) first lateral branch occurred no less than 20 cm from base of stem. These criteria ensured that stems were morphologically similar and could fit easily in the bud vases used for testing. Genotypes were randomly selected for testing (Table 1).

Harvest. The harvest in Expt. 2 followed the same protocol used in Expt. 1 except for the timing of harvest and the amount of time in storage. Due to the closer proximity of Rosemount, MN, to Saint Paul, MN, stems were

Table 1. *Linum* accessions tested in Expt. 2, obtained as seed from the U.S. Department of Agriculture Germplasm Resources Information Network (USDA-GRIN) or the Plant Gene Resources of Canada Genetic Resource Information Network – Canadian Version (GRIN-CA). Accession and plant number combined form the genotype codes referenced throughout (e.g., Ames 29749 #10).

Species	Accession	Plant no.	Seed source
<i>L. austriacum</i>	Ames 29749	10	USDA-GRIN
	Ames 29749	12	USDA-GRIN
	CN 107255	4	GRIN-CA
	CN 107255	17	GRIN-CA
	PI 502410	3	USDA-GRIN
	PI 650293	20	USDA-GRIN
	PI 650294	14	USDA-GRIN
	PI 650295	14	USDA-GRIN
	PI 650299	16	USDA-GRIN
<i>L. lewisii</i>	Ames 31369	15	USDA-GRIN
	Ames 31371	4	USDA-GRIN
	Ames 32565	13	USDA-GRIN
	Ames 32565	17	USDA-GRIN
	CN 107266	5	GRIN-CA
	CN 107266	6	GRIN-CA
	CN 107266	10	GRIN-CA
	PI 650320	5	USDA-GRIN
	PI 650320	13	USDA-GRIN
	PI 522305	3	USDA-GRIN
<i>L. perenne</i>	Ames 21222	16	USDA-GRIN
	CN 107270	5	GRIN-CA
	CN 107270	9	GRIN-CA
	CN 107283	1	GRIN-CA
	CN 19024	8	GRIN-CA
	PI 445972	3	USDA-GRIN
	PI 650328	2	USDA-GRIN
	PI 650328	15	USDA-GRIN

harvested during week 38 (16 Sept. 2019) between 0700 and 1100 HR, transported to St. Paul, and placed in cold storage (4 °C walk-in cooler) by 1200 HR that same day. In contrast to Expt. 1, in which the postharvest tests were initiated the day after harvest (following an overnight storage of stems in the cooler), Expt. 2 was initiated immediately after harvest. In this case, the cut flax stems remained in cold storage for only ≈3 h until all the test vases were set up with solutions (≈1500 h).

Experimental design. The protocols used in both experiments were similar except for the germplasm tested (as noted previously). In Expt. 2, additional measurements were recorded before each stem was processed, including stem length (cm), length to first branch >5 cm (cm), stem diameter at 30 cm from the apex (mm), number of seed pods (capsules), number of previous flowers (as indicated by the number of pedicels, which remain attached even after the flower bud has abscised), and the number of secondary branches. After processing the stems, the number of viable flower buds remaining on each stem was recorded.

Assessments (Expts. 1 and 2)

Vases were checked every 24 h to record the number of flowers open and flower diameter (mm). Open flowers (floral organs visible) were tagged with colored yarn corresponding to each day of the experiment to enable measurement of flower longevity or petal-holding capacity. In Expt. 1, disturbance of individual flowers was minimized when taking measurements, and individual flowers were ended only after >50% petal drop or full-flower abscission. In contrast, in Expt. 2, the stems were tapped three times to remove abscised petals before recording flower longevity each day (Abebie et al., 2008, 2020; Setyadjit et al., 2004). Flower diameter was recorded for any open flower in Expt. 1, whereas in Expt. 2, the flower diameter measurements were limited to flowers in which the petals were fully splayed open.

Vase solutions were changed on a weekly basis, during which time the volume lost (mL) was recorded. Vases containing solution, but no stem, were included as controls to measure the average water loss due to evaporation (mL) for each solution. Using these data, the total water loss (including that lost by evapotranspiration and from stem uptake) was calculated for each vase by subtracting the average rate of solution evaporation. The volume of solution from phloem unloading was not measured and constituted an additional volume in measured water loss. Since each stem had a different vase life, the total water loss was averaged over total vase life to calculate the average daily water loss (mL):

$$\text{Average daily water loss (mL)} =$$

$$\frac{\text{Vase total water loss (mL)} - \text{Control vase avg total water loss (mL)}}{\text{Total Vase Life (no. of days)}}$$

Termination of vase life was based on factors that would cause the average consumer to discard the stem (retail vase life) (Clark et al., 2010). Based on pilot experiments (N. Anderson and D. Tork, unpublished data), reasons for termination commonly observed in perennial flax include leaf wilt, leaf chlorosis, chlorosis localized at the flower buds, and wilt localized at the flower buds (bent neck).

Data analysis. Data were analyzed using independent factorial ANOVAs testing the main effects of location, cultivar, and treatment (Expt. 1); treatment, species, and genotype (Expt. 2) on the following dependent variables: total vase life (d), average number of flowers open, percentage of initial buds opened, average daily water loss (mL), flower diameter (mm), and individual flower longevity (d). Post hoc tests [5% Tukey's honestly significant difference, $\alpha = 0.05$], were only conducted in Expt. 2 for the factors of species and genotype, as all other main effects [treatment, cultivar, location (Expt. 1); treatment (Expt. 2)] consisted of two levels. In Expt. 2, additional independent factorial ANOVAs, along with mean separations, were conducted

to compare the effect of species and genotype on pre-test phenotypic data, which included stem length (cm), length to the first branch (cm), stem diameter (mm), number of previous flowers, number of seed pods, number of viable buds, and number of branches. Pearson correlations (r values) were calculated for all phenotypic traits. Statistical analyses were performed using statistical software [Statistical Package for Social Sciences (SPSS), v. 25 for Windows; SPSS, Inc., Chicago, IL]. Chi-square tests (χ^2) were also conducted to evaluate whether the reasons for termination had an equal frequency within (1:1:1:1 χ^2) and among (1:1 χ^2) treatments, cultivars (1:1:1 χ^2); species.

Results and Discussion

Vase life. In Expt. 1, the effect of treatment on total vase life was highly significant ($P \leq 0.001$; Table 2). The floral preservative solution resulted in a longer vase life compared with the deionized (DI) water control, extending the vase life of both cultivars by >1 d, on average. The main cultivar effect and the cultivar $\times$ treatment interaction, were nonsignificant (Table 2).

Expt. 2 also showed a significant ($P \leq 0.001$) effect of treatment on vase life (Table 3). Pooled across species, the floral preservative treatment resulted in an average increase in vase life of 1.6 d (Table 3). Based on a two-sample t test (two-tailed $\alpha = 0.05$, $P = 0.88$), this was similar to the 1.7-d increase observed among pooled cultivars in Expt. 1 (Table 2). In addition, a significant ($P = 0.04$) species $\times$ treatment interaction was found for vase life, with mean $\pm$ SE differential responses to the floral preservative treatment observed among species: *L. austriacum* had vase life ranging from 7.8 ± 0.4 d (DI water) to 10.4 ± 0.4 d (floral preservative); *L. lewisii* was 8.0 ± 0.4 d to 8.6 ± 0.4 d, whereas *L. perenne* was 8.4 ± 0.4 d to 10.1 ± 0.4 d, respectively. The difference between the floral preservative and DI treatments was greatest for *L. austriacum*. These differences are most likely due to the floral preservative components that

Table 2. Perennial flax cultivars (*L. perenne* 'Blue Flax' and 'Sapphire') tested in Expt. 1, vase solution treatment (DI = deionized, distilled water; FP = floral preservative), and mean vase life (d), number of flowers, percentage of initial flower buds opened, average daily water loss (mL), flower diameter (mm), and individual flower longevity (d). Analysis of variance (ANOVA) results are presented at the base of the table directly below each trait. ANOVA results also include the factor of location, which was not included in the upper part of the table, as it was a NS factor for all traits besides flower diameter.

Cultivar	Treatment	df	Vase life (d)	Flowers (no.)	Flower buds opened (%)	Avg daily water loss (mL)	Flower diam (mm)	Individual flower longevity (d)
Blue Flax	DI		8.5	2.7	24.4	3.9	17.2	3.6
	FP		10.2	6.6	60.8	1.8	19.4	3.3
Sapphire	DI		8.2	2.7	22.8	1.8	15.1	5.3
	FP		9.9	6.7	56.5	1.7	16.2	5.3
Pooled	DI		8.4	2.7	23.7	3.0	16.2	4.4
	FP		10.1	6.6	58.9	1.7	18.0	4.2
Grand mean			9.2	4.7	41.2	2.4	17.2	4.2
ANOVA								
Source of Variation								
Cultivar (C)			NS	NS	NS	***	***	***
Treatment (T)			***	***	***	***	**	NS
Location (L)			NS	NS	NS	NS	*	NS
C $\times$ T			NS	NS	NS	***	NS	NS
C $\times$ L			NS	NS	NS	NS	**	NS
T $\times$ L			NS	NS	NS	NS	NS	NS
C $\times$ T $\times$ L			NS	NS	NS	NS	NS	NS

NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

Table 3. Mean $\pm$ SE trait values in Expt. 2 by treatment (DI = deionized water; FP = floral preservative) and species for vase life (d), number of flowers, percentage of initial flower buds opened, average daily water loss (mL), flower diameter (mm), and individual flower longevity (d).

	n	Vase Life (d)	Flowers (no.)	Flower buds opened (%)	Avg daily water loss (mL)	n	Flower diam (mm)	n	Individual flower longevity (d)
Species									
<i>L. austriacum</i>	54	9.1 $\pm$ 0.3 a ^z	4.2 $\pm$ 0.4 ab	37.2 $\pm$ 2.9 ab	3.2 $\pm$ 0.2 a	32	24.5 $\pm$ 0.7	43	1.3 $\pm$ 0.1
<i>L. lewisii</i>	60	8.3 $\pm$ 0.3 a	3.3 $\pm$ 0.4 a	32.8 $\pm$ 2.8 a	1.8 $\pm$ 0.2 b	31	23.1 $\pm$ 0.7	55	1.3 $\pm$ 0.1
<i>L. perenne</i>	48	9.3 $\pm$ 0.3 a	5.6 $\pm$ 0.5 b	44.9 $\pm$ 3.1 b	2.2 $\pm$ 0.2 b	27	23.8 $\pm$ 0.8	44	1.5 $\pm$ 0.1
Treatment									
DI	81	8.1 $\pm$ 0.2	3.0 $\pm$ 0.4	26.2 $\pm$ 2.4	2.3 $\pm$ 0.2	35	24.3 $\pm$ 0.6	67	1.3 $\pm$ 0.1
FP	81	9.7 $\pm$ 0.2	5.7 $\pm$ 0.4	50.4 $\pm$ 2.4	2.5 $\pm$ 0.2	55	23.3 $\pm$ 0.5	75	1.4 $\pm$ 0.1
Significance									
Species		*	**	*	***		NS		NS
Treatment		***	***	***	NS		NS		NS
Interaction		*	NS	NS	NS		NS		NS
Grand mean	162	8.9 $\pm$ 0.2	4.3 $\pm$ 0.3	38.3 $\pm$ 1.7	2.4 $\pm$ 0.13	90	23.8 $\pm$ 0.4	142	1.4 $\pm$ 0.1

^zMean separations within columns based on Tukey's honestly significant difference results ($\alpha = 0.05$) for significant main effects.

N/A = none available.

NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

enhance postharvest vase life of most cut flower crops (Reid and Jiang, 2012; van Doorn, 1996; Vehniwal and Abbey, 2019), including cestrum (Abbeie et al., 2008); bellflower, pincushion flower, hydrangea (Clark et al., 2010); dahlia (Dole et al., 2009); and sweet pea (Elhindi, 2012).

A significant ($P \leq 0.001$) effect of genotype was also observed for vase life, suggesting that the mean vase life of each species could be improved through breeding and

selection (Table 4). For example, although *L. lewisii* had the shortest average vase life of any species, it contained genotype PI 522305 #3, which had the longest average vase life observed among all genotypes (11.3 d; Table 4). This genotype had performance comparable to all *L. perenne* genotypes, and greater vase life compared with *L. austriacum* genotypes Ames 29749 #12 and PI 502410 #3; *L. lewisii* genotypes Ames 31369 #15, Ames 32565 #17, CN 107266 #10, and PI 650320

#5. Of the species tested, *L. perenne* exhibited the most uniform performance, with no differences observed among genotypes in the species (Table 4).

In both cultivars in Expt. 1, termination of vase life due to flower bud chlorosis was more frequent among DI water compared with floral preservative vases ($P \leq 0.001$); only four floral preservative vases total were ended because of flower bud chlorosis (Table 5). This is likely due to the lack of carbohydrate

Table 4. Mean $\pm$ SE trait values in Expt. 2 on a genotype basis for each species for vase life (d), number of flowers, percentage of initial flower buds opened, average daily water loss (mL), flower diameter (mm), and individual flower longevity (d). The sample numbers (n) varied for the traits examined.

Genotype	n	Vase life (d)	Flowers (no.)	Flower buds opened (%)	Avg daily water loss (mL)	n	Flower diam (mm)	n	Individual flower longevity (d)
<i>L. austriacum</i>									
Ames 29749 #10	6	9.5 $\pm$ 0.7 a-e ^z	4.8 $\pm$ 0.9 a-c	35.5 $\pm$ 8.1 a-c	3.8 $\pm$ 0.5 c-e	4	24.1 $\pm$ 1.3 a-d	5	1.3 $\pm$ 0.3
Ames 29749 #12	6	7.0 $\pm$ 0.7 ab	1.3 $\pm$ 0.9 a	15.7 $\pm$ 8.1 a	4.5 $\pm$ 0.5 de	3	31.5 $\pm$ 1.3 e	4	0.9 $\pm$ 0.4
CN 107255 #4	6	10.0 $\pm$ 0.7 b-e	3.0 $\pm$ 0.9 a	47.3 $\pm$ 8.1 a-c	2.8 $\pm$ 0.5 a-e	0	N/A	4	2.5 $\pm$ 0.4
CN 107255 #17	6	11.2 $\pm$ 0.7 de	3.0 $\pm$ 0.9 a	62.7 $\pm$ 8.1 bc	1.2 $\pm$ 0.5 a-c	5	23.9 $\pm$ 1.0 a-d	6	1.6 $\pm$ 0.3
PI 502410 #3	6	7.3 $\pm$ 0.7 a-c	4.8 $\pm$ 0.9 a-c	28.8 $\pm$ 8.1 a-c	4.8 $\pm$ 0.5 e	4	27.7 $\pm$ 1.3 de	3	1.3 $\pm$ 0.4
PI 650293 #20	6	9.3 $\pm$ 0.7 a-e	3.2 $\pm$ 0.9 a	25.8 $\pm$ 8.1 a-c	2.4 $\pm$ 0.5 a-e	3	22.7 $\pm$ 1.4 a-d	6	1.0 $\pm$ 0.3
PI 650294 #14	6	9.3 $\pm$ 0.7 a-e	3.8 $\pm$ 0.9 ab	39.2 $\pm$ 8.1 a-c	3.1 $\pm$ 0.5 a-e	4	23.5 $\pm$ 1.3 a-d	5	1.5 $\pm$ 0.3
PI 650295 #14	6	8.7 $\pm$ 0.7 a-e	9.3 $\pm$ 0.9 cd	42.8 $\pm$ 8.1 a-c	4.3 $\pm$ 0.5 de	4	24.1 $\pm$ 1.3 a-d	5	1.0 $\pm$ 0.3
PI 650299 #16	6	9.3 $\pm$ 0.7 a-e	4.7 $\pm$ 0.9 a-c	37.0 $\pm$ 8.1 a-c	2.0 $\pm$ 0.5 a-e	5	23.5 $\pm$ 1.0 a-d	5	0.9 $\pm$ 0.3
<i>L. lewisii</i>									
Ames 31369 #15	6	7.3 $\pm$ 0.7 a-c	3.3 $\pm$ 0.9 ab	25.4 $\pm$ 8.1 a-c	3.5 $\pm$ 0.5 b-e	4	20.7 $\pm$ 1.1 a-d	4	2.3 $\pm$ 0.4
Ames 31371 #4	6	9.2 $\pm$ 0.7 a-e	4.5 $\pm$ 0.9 a-c	40.4 $\pm$ 8.1 a-c	3.1 $\pm$ 0.5 a-e	4	23.8 $\pm$ 1.3 a-d	6	1.5 $\pm$ 0.3
Ames 32565 #13	6	9.2 $\pm$ 0.7 a-e	2.5 $\pm$ 0.9 a	23.9 $\pm$ 8.1 ab	0.6 $\pm$ 0.5 a	2	22.3 $\pm$ 1.6 a-d	5	1.3 $\pm$ 0.3
Ames 32565 #17	6	7.0 $\pm$ 0.7 ab	1.8 $\pm$ 0.9 a	24.5 $\pm$ 8.1 ab	2.4 $\pm$ 0.5 a-e	3	19.9 $\pm$ 1.4 ab	6	0.8 $\pm$ 0.3
CN 107266 #5	6	8.5 $\pm$ 0.7 a-e	4.3 $\pm$ 0.9 a-c	29.9 $\pm$ 8.1 a-c	0.9 $\pm$ 0.5 ab	4	27.0 $\pm$ 1.1 c-e	6	1.6 $\pm$ 0.3
CN 107266 #6	6	9.3 $\pm$ 0.7 a-e	3.5 $\pm$ 0.9 ab	36.8 $\pm$ 8.1 a-c	2.5 $\pm$ 0.5 a-e	4	20.2 $\pm$ 1.1 a-c	4	1.6 $\pm$ 0.4
CN 107266 #10	6	7.5 $\pm$ 0.7 a-d	4.5 $\pm$ 0.9 a-c	39.3 $\pm$ 8.1 a-c	1.9 $\pm$ 0.5 a-d	5	25.4 $\pm$ 1.0 b-e	6	1.2 $\pm$ 0.3
PI 650320 #5	6	6.2 $\pm$ 0.7 a	2.0 $\pm$ 0.9 a	26.4 $\pm$ 8.1 a-c	1.0 $\pm$ 0.5 a-c	3	26.2 $\pm$ 1.4 a-d	6	1.3 $\pm$ 0.3
PI 650320 #13	6	7.7 $\pm$ 0.7 a-e	4.2 $\pm$ 0.9 ab	51.2 $\pm$ 8.1 a-c	1.4 $\pm$ 0.5 a-c	2	21.9 $\pm$ 1.6 a-d	6	1.0 $\pm$ 0.3
PI 522305 #3	6	11.3 $\pm$ 0.7 e	2.5 $\pm$ 0.9 a	30.2 $\pm$ 8.1 a-c	0.6 $\pm$ 0.5 a		N/A	6	1.1 $\pm$ 0.3
<i>L. perenne</i>									
Ames 21222 #16	6	8.3 $\pm$ 0.7 a-e	8.3 $\pm$ 0.9 b-d	57.7 $\pm$ 8.1 a-c	2.1 $\pm$ 0.5 a-e	3	23.8 $\pm$ 1.4 a-d	6	1.9 $\pm$ 0.3
CN 107270 #5	6	8.8 $\pm$ 0.7 a-e	1.5 $\pm$ 0.9 a	36.7 $\pm$ 8.1 a-c	2.6 $\pm$ 0.5 a-e	3	26.7 $\pm$ 1.4 b-e	3	0.9 $\pm$ 0.4
CN 107270 #9	6	10.7 $\pm$ 0.7 b-e	3.8 $\pm$ 0.9 ab	32.4 $\pm$ 8.1 a-c	3.0 $\pm$ 0.5 a-e		N/A	5	1.7 $\pm$ 0.3
CN 107283 #1	6	8.2 $\pm$ 0.7 a-e	3.2 $\pm$ 0.9 a	32.5 $\pm$ 8.1 a-c	2.1 $\pm$ 0.5 a-e	6	26.3 $\pm$ 0.9 b-e	6	1.8 $\pm$ 0.3
CN 19024 #8	6	10.8 $\pm$ 0.7 c-e	10.5 $\pm$ 0.9 d	68.9 $\pm$ 8.1 c	1.7 $\pm$ 0.5 a-d	6	17.8 $\pm$ 0.9 a	6	1.5 $\pm$ 0.3
PI 445972 #3	6	9.8 $\pm$ 0.7 a-e	9.3 $\pm$ 0.9 cd	46.8 $\pm$ 8.1 a-c	2.8 $\pm$ 0.5 a-e	2	31.8 $\pm$ 1.6 e	6	1.3 $\pm$ 0.3
PI 650328 #2	6	8.5 $\pm$ 0.7 a-e	3.7 $\pm$ 0.9 ab	36.9 $\pm$ 8.1 a-c	2.5 $\pm$ 0.5 a-e	2	21.8 $\pm$ 1.6 a-d	6	1.5 $\pm$ 0.3
PI 650328 #15	6	8.8 $\pm$ 0.7 a-e	4.2 $\pm$ 0.9 ab	47.0 $\pm$ 8.1 a-c	1.1 $\pm$ 0.5 a-c	4	25.1 $\pm$ 1.3 a-d	6	0.9 $\pm$ 0.3
Significance									
Genotype		***	***	***	***		***		NS
Treatment		***	***	***	NS		***		NS
Interaction		NS	*	NS	*		*		NS

^zMean separations within columns based on Tukey's honestly significant difference results ($\alpha = 0.05$) for significant main effects.

N/A = none available.

NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

Table 5. Reason for termination of vase life by cultivar (Blue Flax and Sapphire) and treatment (DI = deionized water, FP = floral preservative) in Expt. 1. Chi-square tests for equal distribution of termination reason, within (1:1:1:1 χ^2) and among (1:1 χ^2) treatments and cultivars.

Subset	Reason for termination of vase life				1:1:1:1 χ^2 (df = 3)
	Flower bud chlorosis	Flower bud wilt	Leaf chlorosis	Leaf wilt	
Blue Flax					
DI	45	6	2	1	99.04 ***
FP	3	29	18	4	34.15***
1:1 χ^2 among treatments (df = 1)	36.75***	15.11***	12.8***	1.8 ^{NS}	
Sapphire					
DI	34	6	0	6	68.72***
FP	1	18	15	9	15.69**
1:1 χ^2 among treatments (df = 1)	31.11***	6.00*	15.00***	3.00*	
Both cultivars (treatments pooled)					
Blue Flax	48	35	20	5	38.44***
Sapphire	35	24	15	12	14.93**
Pooled	83	59	35	17	51.03***
1:1 χ^2 among cultivars (df = 1)	0.16 ^{NS}	0.32 ^{NS}	0.03 ^{NS}	4.74*	

NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

nutrients in the DI water solution, which are often required for postharvest development of flower buds (Reid and Jiang, 2012; van Doorn, 1996; Vehniwal and Abbey, 2019). For both cultivars, the floral preservative treatment had a greater proportion of terminations due to flower bud wilt and leaf chlorosis compared with the DI water treatment (Table 5). Combined, flower bud wilt and leaf chlorosis accounted for 87% of vase life terminations among the ‘Blue Flax’ floral preservative group, and 77% of all terminations among the ‘Sapphire’ floral preservative group. Leaf wilt was the least frequently observed termination reason overall, although it was more frequent in ‘Sapphire’ than in ‘Blue Flax’ ($P \leq 0.05$; Table 5).

As with Expt. 1, leaf wilt was the least frequently observed termination reason among all species and treatment combinations in Expt. 2 (Table 6). All three species (treatments pooled) had similar distributions of termination symptoms, except for flower bud wilt, which was less frequent in *L. perenne* ($P \leq 0.05$; Table 6). For *L. austriacum*, the

frequency of termination symptoms did not change based on treatment (nonsignificant 1:1 χ^2), although, like the other species, some reasons for termination were observed more or less frequently overall (significant 1:1:1:1 χ^2 ; Table 6). In contrast, both *L. lewisii* and *L. perenne* had a greater incidence of flower bud chlorosis for the DI water treatment ($P \leq 0.01$), and a greater incidence of leaf chlorosis for the floral preservative treatment ($P \leq 0.01$; Table 6).

Number of flowers. In Expt. 1, there was a significant effect of treatment ($P \leq 0.001$) on the total number of flowers observed (Table 2). Vases with floral preservative solution had more than two times the number of flowers compared with DI water vases. The main effect of cultivar, and the cultivar $\times$ treatment interaction were nonsignificant (Table 2).

In Expt. 2, there was a significant effect of species ($P \leq 0.01$) and treatment ($P \leq 0.001$) on the number of flowers per stem (Table 3). On average, 5.7 flowers per stem

were observed for the floral preservative treatment, whereas 3.0 flowers per stem were observed for DI water vases (Table 3). Among species, *L. perenne* had the greatest average number of flowers per stem (5.6), followed by *L. austriacum* (4.2), and *L. lewisii* (3.3; Table 3).

In Expt. 2, there was also a significant effect of genotype on the number of flowers per stem (Table 4). Breeding for cut flower performance cannot be evaluated based on vase life alone. For example, *L. lewisii* genotype “PI 522305 #3” and *L. austriacum* genotype “CN 107255 #17” outperformed several other genotypes in terms of vase life, but had fewer flowers compared with *L. austriacum* genotype PI 650295 #14, and *L. perenne* genotypes Ames 21222 #16, CN 19024 #8, and PI 445972 #3 (Table 4). Furthermore, the genotype with the greatest number of flowers, *L. perenne* CN 19024 #8, also had a mean vase life greater than several genotypes, including *L. austriacum* Ames 29749 #12, and *L. lewisii* Ames 32565 #15 and PI

Table 6. Reason for termination of vase life in Expt. 2 by species (*L. austriacum*, *L. lewisii*, *L. perenne*) and treatment (DI = deionized water, FP = floral preservative). Chi-square tests for equal distribution of termination reason, within (1:1:1:1 χ^2) and among (1:1 χ^2) treatments and among (1:1:1 χ^2) species.

Subset	Reason for termination of vase life				1:1:1:1 χ^2 (df = 3)
	Flower bud chlorosis	Flower bud wilt	Leaf chlorosis	Leaf wilt	
<i>L. austriacum</i>					
DI	8	14	4	1	14.04**
FP	3	15	8	1	17.30***
1:1 χ^2 among treatments (df = 1)	2.27 ^{NS}	0.03 ^{NS}	1.33 ^{NS}	0.00 ^{NS}	
<i>L. lewisii</i>					
DI	11	14	5	0	15.60***
FP	2	7	21	0	35.87***
1:1 χ^2 among treatments (df = 1)	6.23**	2.33 ^{NS}	9.85**	N/A	
<i>L. perenne</i>					
DI	12	6	6	0	12.00**
FP	1	4	18	1	33.00***
1:1 χ^2 among treatments (df = 1)	9.31**	0.40 ^{NS}	6.00**	1.00 ^{NS}	
All species (treatments pooled)					
<i>L. austriacum</i>	11	29	12	2	28.22***
<i>L. lewisii</i>	13	21	26	0	25.73***
<i>L. perenne</i>	13	10	24	1	22.50***
Pooled	37	60	62	3	55.83***
1:1:1 χ^2 among species (df = 1)	0.56 ^{NS}	7.52*	5.76 ^{NS}	2.13 ^{NS}	

NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

650320 #5 (Table 4). Altogether, these results highlight the importance of selecting for improved postharvest floral development (measured as number of flowers), in addition to vase life.

Percentage of flower buds opened. In Expt. 1, there was a significant effect of treatment ($P \leq 0.001$) on the percentage of flower buds opened (Table 2). On average, the floral preservative treatment resulted in $\approx 59\%$ of buds opened, whereas only $\approx 24\%$ of buds opened in the DI water treatment (Table 2). The effects of cultivar, and the cultivar $\times$ treatment interaction, were nonsignificant for percentage of flower buds opened (Table 2).

In Expt. 2, similar results to the total number of flowers per stem were recorded. There was a significant effect of treatment ($P \leq 0.001$) and species ($P \leq 0.05$) on the percentage of initial buds opened (Table 3). The floral preservative treatment resulted in a greater percentage of flower buds opened per stem (50.4%) compared with the DI water control (26.2%). Among species, *L. perenne* had the greatest percentage of flower buds opened (44.9%), followed by *L. austriacum* (37.2%) and *L. lewisii* (32.8%; Table 3). There was also a significant effect of genotype on percentage of flower buds opened, although post hoc tests revealed that most genotypes were similar (Table 4). Most notably, the genotype with the greatest number of flowers, *L. perenne* CN 19024 #8, also had the highest percentage of flower buds opened, indicating that this genotype had superior postharvest floral development, and not just a greater number of initial buds (Table 4). Thus, percentage of flower buds opened should always be considered alongside the total number of flowers when selecting for improved postharvest floral development in perennial flax.

Average daily water loss. In Expt. 1, there was a significant cultivar $\times$ treatment interaction for the average daily water loss ($P \leq 0.001$; Table 2). Cultivar Sapphire had similar daily water loss across the treatments, whereas the Blue Flax floral preservative treatment averaged more than two times the rate of water loss compared with the DI water treatment (Table 2). It is difficult to discern the cause of this interaction, especially given that average daily water loss was not correlated with any trait besides percentage of flower buds opened ($r = -0.215$, $P \leq 0.01$; Table 8).

In Expt. 2, there was a significant effect of species on average daily water loss ($P \leq 0.001$); greater water loss was observed for *L. austriacum* (3.2 mL/d) compared with *L. perenne* (2.2 mL/d) and *L. lewisii* (1.8 mL/d; Table 3). Among genotypes, daily water loss mean values ranged from 0.6 mL/d (*L. lewisii*; Ames 32565 #13) to 4.8 mL/d (*L. austriacum*; PI 502410 #3) (Table 4).

Flower diameter. In Expt. 1, a significant effect of cultivar ($P \leq 0.001$) and treatment ($P \leq 0.01$) on flower diameter was observed (Table 2). Cultivar Sapphire had a consistently smaller flower diameter compared with Blue Flax (Table 2). The floral preservative treatment resulted in larger flower diameter,

Fig. 1. Mean $\pm$ SE flower diameter (mm) values showing interaction of treatment (DI = deionized water; FP = floral preservative) and genotype. Genotypes are sorted based on mean DI flower diameter.

irrespective of cultivar, indicating that the floral preservative improved postharvest floral development. The main effect of location ($P \leq 0.05$), and the cultivar $\times$ location interaction ($P \leq 0.01$) were also significant (Table 2). ‘Blue Flax’ stems from the Grand Rapids location had larger average flower diameter (mean $\pm$ SE; 19.7 ± 0.3) compared with the Morris location (17.9 ± 0.3). Conversely, ‘Sapphire’ was observed to have larger flower diameter for stems from Morris (16.1 ± 0.2) compared with Grand Rapids (15.3 ± 0.3).

In Expt. 2, a significant ($P \leq 0.05$) genotype $\times$ treatment interaction on flower diameter was observed (Table 4, Fig. 1). The sample size (n) for flower diameter observations varied because flowers were only measured once fully open, and petal drop sometimes occurred before the measurement could be recorded (Table 4). *L. perenne* contained the genotypes with the largest (31.8 mm; PI 445972 #3) and the smallest (17.8 mm; CN 19024 #8) mean flower diameters observed in the study. Despite having the longest vase life and greatest number of flowers, the small flower diameter of CN 19024 #8

detracts from the ornamental value of this genotype. Depending on the goals for selection, it may instead be more advantageous to favor a genotype such as PI 445972 #3, which has a similar vase life and number of flowers as CN 19024 #8, but a significantly larger flower diameter (Table 4). This example further illustrates the importance of considering multiple traits during selection for cut flower performance.

Individual flower longevity. In Expt. 1, there was a significant ($P \leq 0.001$) effect of cultivar on individual flower longevity; ‘Sapphire’ had an individual flower longevity ≈ 2 d longer than ‘Blue Flax’, on average (Table 2). No other factors, or their interactions, affected flower longevity (Table 2). Finger taps were added to the experimental protocol in 2019 because the flower longevity observed in 2018 was not representative of field observations (data not shown), in which petal drop occurred approximately midday. Perennial flax are known to produce new flowers every morning, followed by petal drop in the afternoon (Addicott, 1977; Eastman, 1968; Vaisey-Genser and Morris,

Table 7. Pearson correlation coefficients (r) among all traits measured in Expt. 1, including vase life (d), number of flowers, percentage of initial flower buds opened, average daily water loss (mL), flower diameter (mm), and individual flower longevity (d).

Trait	Vase life	Flowers (no.)	Flower buds opened (%)	Avg daily water loss	Flower diam	Individual flower longevity
Vase life	1.0					
Flowers (no.)	0.405***	1.0				
Flower buds opened (%)	0.448***	0.720***	1.0			
Avg daily water loss	-0.048	-0.109	-0.215**	1.0		
Flower diam	0.149	0.125	0.224**	0.006	1.0	
Individual flower longevity	0.330***	-0.002	-0.023	-0.116	-0.346***	1.0

***Significant at $P \leq 0.001$ (two-tailed $\alpha = 0.05$).

Table 8. Pearson correlation coefficients (r) for all traits measured in Expt. 2, including vase life (d), number of flowers, percentage of initial flower buds opened, average daily water loss (mL), flower diameter (mm), individual flower longevity (d), stem length (cm), length to the first branch (cm), stem diameter (mm), number of previous flowers (based on pedicel count), number of seed pods, number of viable flower buds, and number of branches at the apex of the stem.

Trait	Vase life	Flowers (no.)	Flower buds opened (%)	Avg daily water loss	Flower diam	Individual flower longevity	Stem length	Length to first branch	Stem diam	Previous flowers (no.)	Seed pods (no.)	Viable buds (no.)	Branches (no.)
Vase life	1.0												
Flowers (no.)	0.325***	1.0											
Flower buds opened (%)	0.476***	0.674***	1.0										
Avg daily water loss	-0.170*	0.234**	-0.039	1.0									
Flower diam	-0.212*	-0.202	-0.270*	0.020	1.0								
Individual flower longevity	0.367***	0.131	0.304***	-0.032	0.042	1.0							
Stem length	-0.014	0.083	-0.016	0.422***	-0.027	0.113	1.0						
Length to first branch	0.166*	-0.140	0.064	-0.033	-0.108	-0.062	0.660***	1.0					
Stem diam	-0.019	0.147	-0.010	0.496***	-0.113	0.129	0.455***	0.188*	1.0				
Previous flowers (no.)	-0.146	0.281***	0.030	0.558***	-0.002	0.042	0.337***	-0.213**	0.325***	1.0			
Seed pods (no.)	-0.154	0.178*	-0.015	0.533***	0.026	-0.039	0.303***	-0.145	0.298***	0.911***	1.0		
Viable buds (no.)	-0.066	0.474***	-0.162*	0.459***	0.057	-0.068	0.200*	-0.282***	0.285***	0.397***	0.298***	1.0	
Branches (no.)	-0.113	0.275***	-0.059	0.585***	0.048	0.073	0.296***	-0.231**	0.365***	0.684***	0.550***	0.576***	1.0

*, **, ***Significant at $P \leq 0.05$, 0.01, and 0.001, respectively (two-tailed $\alpha = 0.05$).

2003). In addition, flower longevity had a strong negative correlation with flower diameter in 2018 ($r = -0.346$, $P \leq 0.001$) (Table 7). This link to flower diameter might partially explain the difference in flower longevity between the two cultivars. The larger petals of 'Blue Flax' had greater surface area for evapotranspiration, which could have encouraged rapid petal drop. Further studies would be required to determine the exact cause(s) of this petal drop.

Interestingly, in Expt. 2, individual flower longevity (d) was not significant for any factor, and a grand mean of 1.4 d was observed (Table 3). Flower longevity data have not yet been measured in the field, but anecdotally, flowers of perennial flax tend to open in the morning at ≈ 0600 – 0700 HR and drop by mid-afternoon, between 1300 and 1700 HR, which is consistent with a previous report on flower abscission in *L. lewisii* (Addicott, 1977). Therefore, even with finger taps added to the protocol, the individual flower longevity is still longer than expected based on field observations. Selection of genotypes that hold their petals late into the afternoon would be critical to increase vase life of individual flowers. Overall, the lack of variation among genotypes for individual flower longevity poses one of the greatest challenges for selection of improved cut flower flax (Table 4).

Trait correlations. In Expt. 1, correlations ($P \leq 0.001$) were observed between vase life and number of flowers ($r = 0.405$), percentage of initial buds opened ($r = 0.448$), and individual flower longevity ($r = 0.330$; Table 7). This suggests a logical relationship between the overall health of the stem and postharvest floral development. The high correlation coefficient for average number of flowers and the percentage of initial buds opened ($r = 0.720$, $P \leq 0.001$) may be explained by the fact that total number of flowers is one of the inputs for the calculation of percentage of flower buds opened. It is difficult to interpret the correlation ($P \leq 0.01$) between flower diameter and percentage of flower buds opened, but potential factors include increased mean trait values in 'Blue Flax' compared with 'Sapphire,' or because of the increased trait values in the floral preservative treatment compared with the DI water treatment (Table 2).

In Expt. 2, vase life was correlated ($P \leq 0.001$) with the number of flowers ($r = 0.325$), the percentage of flower buds opened ($r = 0.476$), and individual flower longevity ($r = 0.367$; Table 8). The connection among vase life, number of flowers, and percentage of buds open is probably because stems with a longer vase life have more time for floral development. Negative correlations ($P \leq 0.05$) were also found between vase life and both average daily water loss ($r = -0.170$) and flower diameter ($r = -0.212$; Table 8). Average daily water loss was positively correlated ($r = 0.234$, $P \leq 0.01$) with number of flowers, logically indicating that floral development increases water use and transpiration (Table 8). The number of flowers was again correlated ($r = 0.674$, $P \leq 0.001$) with the

Table 9. Mean $\pm$ SE trait values on a species basis for traits measured at the start of Expt. 2 including stem length (cm), length to the first branch (cm), stem diameter (mm), number of previous flowers (based on pedicel count), number of seed pods, number of viable flower buds, and number of branches at the apex of the stem. The sample numbers (n) varied by species.

Species	n	Stem length (cm)	Length to first branch (cm)	Stem diam (mm)	Previous flowers (no.)	Seed pods (no.)	Viable buds (no.)	Branches at apex (no.)
<i>L. austriacum</i>	54	44.9 $\pm$ 1.2	32.8 $\pm$ 1.1	2.0 $\pm$ 0.0 b ^z	10.9 $\pm$ 1.5	4.7 $\pm$ 1.0	13.7 $\pm$ 0.9 b	5.80 $\pm$ 0.34 b
<i>L. lewisii</i>	60	44.3 $\pm$ 1.1	33.4 $\pm$ 1.0	1.8 $\pm$ 0.0 a	8.4 $\pm$ 1.4	3.7 $\pm$ 0.9	10.4 $\pm$ 0.8 a	4.27 $\pm$ 0.32 a
<i>L. perenne</i>	48	46.9 $\pm$ 1.3	35.0 $\pm$ 1.2	1.9 $\pm$ 0.0 ab	13.1 $\pm$ 1.6	5.3 $\pm$ 1.0	12.1 $\pm$ 0.9 ab	5.23 $\pm$ 0.32 ab
Significance		NS	NS	*	NS	NS	*	**
Grand mean	162	45.4 $\pm$ 0.7	33.7 $\pm$ 0.6	1.9 $\pm$ 0.0	10.8 $\pm$ 0.9	4.6 $\pm$ 0.6	12.1 $\pm$ 0.5	5.1 $\pm$ 0.2

^zMean separations within columns based on Tukey's honestly significant difference results ($\alpha = 0.05$) for significant main effects.

NS, *, **Nonsignificant or significant at $P \leq 0.05$ or 0.01, respectively.

percentage of flower buds opened (Table 8). Interestingly, the only correlations ($P \leq 0.001$) with flower longevity were with total vase life ($r = 0.367$) and percentage of initial buds open ($r = 0.304$; Table 8), and there was not a correlation between flower diameter and flower longevity like in Expt. 1 (Table 7).

Indirect selection for postharvest traits. In Expt. 2, attempts to find an easily recorded phenotypic trait that correlated with postharvest outcomes had mixed results. Of the traits measured at the start of the experiment, only the length to the first branch showed correlation with vase life ($r = 0.166$, $P \leq 0.05$; Table 8). In contrast, several traits showed positive correlation ($P \leq 0.001$) with the number of flowers, including the number of previous flowers ($r = 0.281$), the number of viable buds ($r = 0.474$), the number of branches ($r = 0.275$), and the number of seed pods

($r = 0.178$, $P \leq 0.05$; Table 8). In addition, the number of branches and the number of viable buds were correlated ($r = 0.576$, $P \leq 0.001$; Table 8). Taken together, these results suggest that selection for genotypes with a greater length to the first branch, but a larger number of branches would increase the number of flowers per stem, and perhaps even positively affect vase life.

Positive correlations ($P \leq 0.001$) with average daily water loss were observed for all traits measured at the start of the experiment except for the length to the first branch (Table 8). It makes logical sense that stems with greater length, diameter, number of seed pods, number of viable buds, and number of branches would require greater daily water intake. The positive correlation ($r = 0.558$, $P \leq 0.001$) between daily water loss and

number of previous flowers is more difficult to interpret, because all that remains attached to the stem from previous flowers is a small ≈ 1 - to 2-cm pedicel. The positive correlations ($P \leq 0.001$) observed between number of previous flowers and stem length ($r = 0.337$) and stem diameter ($r = 0.325$) suggest that number of previous flowers is related to the size of the stem, which may explain the correlation with average daily water loss (Table 8). Alternatively, positive correlation ($r = 0.281$, $P \leq 0.001$) between the number of previous flowers and number of flowers opened during the experiment may simply indicate that a greater number of previous flowers is reflective of a healthier, more reproductive stem, which then has more postharvest floral development and therefore more water use.

Overall, the high degree of correlation among most of these initial morphological

Table 10. Mean $\pm$ SE trait values on a genotype basis for traits measured at the start of Expt. 2 including stem length (cm), length to the first branch (cm), stem diameter (mm), number of previous flowers (based on pedicel count), number of seed pods, number of viable flower buds, and number of branches at the apex of the stem. The sample number (n = 6) was consistent across genotypes.

Genotype	Stem length (cm)	Length to first branch (cm)	Stem diam (mm)	Previous flowers (no.)	Seed pods (no.)	Viable buds (no.)	Branches (no.)
<i>L. austriacum</i>							
Ames 29749 #10	57.5 $\pm$ 2.3 gh ^z	37.2 $\pm$ 1.9 c-f	2.0 $\pm$ 0.1 a-c	9.0 $\pm$ 4.2 a	4.0 $\pm$ 2.7 ab	18.8 $\pm$ 2.1 d-f	7.8 $\pm$ 1.0 a
Ames 29749 #12	45.5 $\pm$ 2.3 b-g	28.3 $\pm$ 1.9 a-c	1.8 $\pm$ 0.1 a-c	14.8 $\pm$ 4.2 a	3.2 $\pm$ 2.7 ab	12.0 $\pm$ 2.1 a-f	5.0 $\pm$ 1.0 a
CN 107255 #4	50.8 $\pm$ 2.3 d-h	36.8 $\pm$ 1.9 c-e	2.2 $\pm$ 0.1 c	12.5 $\pm$ 4.2 a	5.0 $\pm$ 2.7 ab	6.3 $\pm$ 2.1 a-c	6.7 $\pm$ 1.0 a
CN 107255 #17	50.3 $\pm$ 2.3 c-h	45.7 $\pm$ 1.9 e-g	1.8 $\pm$ 0.1 a-c	9.7 $\pm$ 4.2 a	5.7 $\pm$ 2.7 ab	5.5 $\pm$ 2.1 ab	4.0 $\pm$ 1.0 a
PI 502410 #3	40.2 $\pm$ 2.3 a-d	24.8 $\pm$ 1.9 a	1.9 $\pm$ 0.1 a-c	23.8 $\pm$ 4.2 a	15.3 $\pm$ 2.7 b	17.0 $\pm$ 2.1 c-f	7.2 $\pm$ 1.0 a
PI 650293 #20	41.2 $\pm$ 2.3 a-d	31.7 $\pm$ 1.9 a-d	2.0 $\pm$ 0.1 a-c	12.2 $\pm$ 4.2 a	5.5 $\pm$ 2.7 ab	12.3 $\pm$ 2.1 a-f	5.0 $\pm$ 1.0 a
PI 650294 #14	43.8 $\pm$ 2.3 a-f	35.3 $\pm$ 1.9 b-e	2.3 $\pm$ 0.1 c	3.7 $\pm$ 4.2 a	1.5 $\pm$ 2.7 ab	15.5 $\pm$ 2.1 a-f	4.0 $\pm$ 1.0 a
PI 650295 #14	42.2 $\pm$ 2.3 a-e	30.3 $\pm$ 1.9 a-d	2.1 $\pm$ 0.1 a-c	7.0 $\pm$ 4.2 a	1.5 $\pm$ 2.7 ab	22.2 $\pm$ 2.1 f	7.0 $\pm$ 1.0 a
PI 650299 #16	32.8 $\pm$ 2.3 a	25.0 $\pm$ 1.9 ab	1.7 $\pm$ 0.1 a	5.5 $\pm$ 4.2 a	0.7 $\pm$ 2.7 a	13.2 $\pm$ 2.1 a-f	5.5 $\pm$ 1.0 a
<i>L. lewisii</i>							
Ames 31369 #15	48.2 $\pm$ 2.3 c-h	35.8 $\pm$ 1.9 c-e	1.9 $\pm$ 0.1 a-c	6.5 $\pm$ 4.2 a	3.3 $\pm$ 2.7 ab	11.8 $\pm$ 2.1 a-f	4.5 $\pm$ 1.0 a
Ames 31371 #4	42.0 $\pm$ 2.3 a-e	24.2 $\pm$ 1.9 a	2.0 $\pm$ 0.1 a-c	15.0 $\pm$ 4.2 a	8.7 $\pm$ 2.7 ab	10.8 $\pm$ 2.1 a-f	3.3 $\pm$ 1.0 a
Ames 32565 #13	35.2 $\pm$ 2.3 ab	27.8 $\pm$ 1.9 a-c	1.6 $\pm$ 0.1 a	7.0 $\pm$ 4.2 a	2.3 $\pm$ 2.7 ab	10.2 $\pm$ 2.1 a-e	4.7 $\pm$ 1.0 a
Ames 32565 #17	43.5 $\pm$ 2.3 a-f	36.8 $\pm$ 1.9 c-e	1.9 $\pm$ 0.1 a-c	9.2 $\pm$ 4.2 a	5.2 $\pm$ 2.7 ab	7.8 $\pm$ 2.1 a-d	4.8 $\pm$ 1.0 a
CN 107266 #5	44.3 $\pm$ 2.3 a-f	32.0 $\pm$ 1.9 a-d	1.7 $\pm$ 0.1 a	2.3 $\pm$ 4.2 a	0.0 $\pm$ 2.7 a	14.7 $\pm$ 2.1 a-f	4.0 $\pm$ 1.0 a
CN 107266 #6	54.8 $\pm$ 2.3 f-h	47.5 $\pm$ 1.9 fg	2.0 $\pm$ 0.1 a-c	9.0 $\pm$ 4.2 a	5.8 $\pm$ 2.7 ab	9.0 $\pm$ 2.1 a-d	4.0 $\pm$ 1.0 a
CN 107266 #10	57.2 $\pm$ 2.3 gh	38.8 $\pm$ 1.9 d-f	1.7 $\pm$ 0.1 ab	11.5 $\pm$ 4.2 a	1.8 $\pm$ 2.7 ab	12.3 $\pm$ 2.1 a-f	5.7 $\pm$ 1.0 a
PI 650320 #5	40.2 $\pm$ 2.3 a-d	31.2 $\pm$ 1.9 a-d	1.7 $\pm$ 0.1 a	5.0 $\pm$ 4.2 a	1.7 $\pm$ 2.7 ab	9.0 $\pm$ 2.1 a-d	4.0 $\pm$ 1.0 a
PI 650320 #13	39.3 $\pm$ 2.3 a-d	30.5 $\pm$ 1.9 a-d	1.9 $\pm$ 0.1 a-c	11.2 $\pm$ 4.2 a	5.0 $\pm$ 2.7 ab	8.8 $\pm$ 2.1 a-d	3.8 $\pm$ 1.0 a
PI 522305 #3	38.0 $\pm$ 2.3 a-c	29.0 $\pm$ 1.9 a-d	1.8 $\pm$ 0.1 a-c	7.5 $\pm$ 4.2 a	3.2 $\pm$ 2.7 ab	9.8 $\pm$ 2.1 a-d	3.8 $\pm$ 1.0 a
<i>L. perenne</i>							
Ames 21222 #16	45.2 $\pm$ 2.3 a-g	34.2 $\pm$ 1.9 a-d	1.9 $\pm$ 0.1 a-c	9.5 $\pm$ 4.2 a	1.2 $\pm$ 2.7 ab	14.0 $\pm$ 2.1 a-f	4.8 $\pm$ 1.0 a
CN 107270 #5	39.7 $\pm$ 2.3 a-d	33.5 $\pm$ 1.9 a-d	1.8 $\pm$ 0.1 a-c	8.2 $\pm$ 4.2 a	2.8 $\pm$ 2.7 ab	4.5 $\pm$ 2.1 a	5.8 $\pm$ 1.0 a
CN 107270 #9	60.5 $\pm$ 2.3 h	52.8 $\pm$ 1.9 g	2.2 $\pm$ 0.1 bc	9.2 $\pm$ 4.2 a	3.0 $\pm$ 2.7 ab	10.7 $\pm$ 2.1 a-e	4.5 $\pm$ 1.0 a
CN 107283 #1	54.3 $\pm$ 2.3 e-h	37.3 $\pm$ 1.9 c-f	2.0 $\pm$ 0.1 a-c	16.8 $\pm$ 4.2 a	8.8 $\pm$ 2.7 ab	10.3 $\pm$ 2.1 a-e	4.0 $\pm$ 1.0 a
CN 19024 #8	44.5 $\pm$ 2.3 a-f	29.0 $\pm$ 1.9 a-d	1.9 $\pm$ 0.1 a-c	21.8 $\pm$ 4.2 a	7.0 $\pm$ 2.7 ab	16.2 $\pm$ 2.1 b-f	7.0 $\pm$ 1.0 a
PI 445972 #3	48.3 $\pm$ 2.3 c-h	29.0 $\pm$ 1.9 a-d	1.9 $\pm$ 0.1 a-c	23.2 $\pm$ 4.2 a	11.2 $\pm$ 2.7 ab	21.3 $\pm$ 2.1 ef	7.0 $\pm$ 1.0 a
PI 650328 #2	43.2 $\pm$ 2.3 a-f	30.2 $\pm$ 1.9 a-d	1.8 $\pm$ 0.1 a-c	11.0 $\pm$ 4.2 a	6.5 $\pm$ 2.7 ab	10.8 $\pm$ 2.1 a-f	4.3 $\pm$ 1.0 a
PI 650328 #15	39.8 $\pm$ 2.3 a-d	33.8 $\pm$ 1.9 a-d	1.6 $\pm$ 0.1 a	5.2 $\pm$ 4.2 a	2.2 $\pm$ 2.7 ab	9.2 $\pm$ 2.1 a-d	4.3 $\pm$ 1.0 a
Significance	***	***	***	*	*	***	*

^zMean separations within columns based on Tukey's honestly significant difference results ($\alpha = 0.05$) for significant main effects.

*, ***Significant at $P \leq 0.05$ or 0.001, respectively.

measurements indicates redundancy, suggesting that several of these measurements should be dropped in future experiments. For example, the number of previous flowers is highly correlated with the number of branches ($r = 0.684$, $P \leq 0.001$), and both traits show similar levels of correlation with average daily water loss, and the number of flowers (Table 8). Similarly, the number of previous flowers and the number of seed pods are highly correlated ($r = 0.911$, $P \leq 0.001$) and have similar levels of correlation with other traits. Therefore, future experiments could benefit from including one of these initial measurements, but not all three.

There was a significant effect of species on the number of branches ($P \leq 0.01$), stem diameter ($P \leq 0.05$), and the number of viable buds ($P \leq 0.05$; Table 9). A significant effect of genotype was observed for stem length ($P \leq 0.001$), length to the first branch ($P \leq 0.001$), stem diameter ($P \leq 0.001$), number of viable buds ($P \leq 0.001$), number of previous flowers ($P \leq 0.05$), number of seed pods ($P \leq 0.05$), and number of branches ($P \leq 0.05$; Table 10). The species *L. austriacum* possessed a greater average stem diameter, number of branches, and number of viable buds compared with *L. lewisii*; for all these traits, *L. perenne* was intermediate and did not differ from either species (Table 9).

Differences were observed among genotypes for all traits except the number of previous flowers and the number of branches (Table 10). These data present an opportunity to select genotypes with favorable combinations of stem phenotype and cut flower performance. For example, *L. perenne* genotype CN 107270 #9 had a greater stem length and length to the first branch compared with many of the other genotypes tested, making it superior for use in floral designs (Table 10); this genotype also has an average vase life that is 1.4 d greater than the mean vase life for *L. perenne* (Tables 3 and 4).

Conclusions

Perennial flax has the potential to perform well as a cut flower crop that can be used as a filler material to add vibrant true blue color to floral arrangements (Fig. 2). Based on this study, we recommend placing stems of *L. perenne* or *L. austriacum* in a floral preservative that is changed at least one time per week. If following this approach, the average expected vase life of ≈ 9 d meets industry standards (T. Nell, personal communication), and four to five flowers per stem can be expected to open over that duration. Based on the variation observed among genotypes in this study, it would be possible, through selection, to increase the average vase life of perennial flax to more than 11 d, with more than 10.5 flowers per stem.

The proclivity toward rapid petal drop introduces challenges for both retail and wholesale florists, who need to be sure that their products are in peak condition at the

Fig. 2. Example floral design using flax (blue flowers; arrows) as a filler crop to add color. Floral design credit: N. Anderson; photo credit: D. Tork.

time of sale or presentation. This is an important issue for the introduction of new specialty cut flower crops into the market, as noted in other crops. The issue of petal drop can be avoided by harvesting stems late in the growing season after seed set has occurred, but before capsule maturity. In the first year of growth, this usually occurs from August to September; in the second year, the green boll stage may come as early as June. The round green seed capsules transform flax into a different kind of filler material, by contributing a unique texture rather than color (Fig. 3).

The morphological similarities among *L. austriacum*, *L. perenne*, and *L. lewisii*, and their potential for hybridization, suggest that a cautious approach should be taken when interpreting species comparisons (Jhala et al., 2008; Ockendon, 1968, 1971; Pendleton et al., 2008; Seetharam, 1972). There could be significant error introduced if any of the accessions were misclassified during the curation process—a problem that could be remedied in future studies by using single nucleotide polymorphism markers to define

Fig. 3. Example floral design using flax as a filler crop to add texture (round green seed capsules). Floral design credit: N. Anderson; photo credit: D. Tork.

genetic relationships. From a breeder's perspective, this potential to hybridize is still a positive attribute, as it introduces the possibility of capturing the best traits from all three species within a general perennial flax breeding program.

The specific and genotypic differences observed in this study will enable selections for improved cut flower performance that advance the goal of developing new cut flower flax varieties. This study also contributes to the body of knowledge about the ornamental potential of various wild flax species, which should prove useful to future ornamental *Linum* breeders.

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