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Fabric Containers Increased Irrigation Demand but Decreased Leachate Loss of Nitrogen and Phosphorus Compared With Conventional Plastic Containers During Production of Dwarf Burford Holly

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Abstract. **Fabric containers (FAB), due to their root-pruning properties, can be used as an alternative to conventional plastic containers (PLA) in container nurseries. Because sidewall evaporation in FAB has been shown to reduce container substrate temperatures, our objective was to determine if FAB would reduce the release rate of controlled-release fertilizer (CRF), resulting in less leachate loss of nitrogen (N) and phosphorus (P) and greater CRF longevity. Dwarf Burford holly were grown in 36-cm-diameter (18-L substrate) FAB or PLA in a bark-peat substrate with incorporated CRF. Spray stake irrigation was routinely adjusted to a target leaching fraction of 25%. Maximum daily substrate temperature, measured 3 cm from southwest-facing container wall, averaged 6 °C lower in FAB than in PLA. For two 31-week experiments where leachate was continuously collected and sampled weekly, FAB reduced leachate N loss by 30% and P loss by 47% despite requiring 66% more irrigation water and collecting 31% more leachate than with PLA. FAB reduced average N loss from 114 to 78 kg·ha^{-1} and average P loss from 16.0 to 8.6 kg·ha^{-1}. FAB increased plant size by 8% and shoot dry weight by 12% for one experiment but had no effect in the other. We concluded that compared with PLA, the use of FAB can decrease leachate loss of N and P but require considerably more irrigation water to offset water loss via sidewall evaporation.**

Outdoor production of plants in containers requires frequent irrigation, typically daily or multiple times per day, resulting in container drainage that is often >20% of irrigation water applied. To improve fertilizer efficiency and reduce runoff loss of applied nutrients, nurseries use controlled-release fertilizer (CRF). CRFs consist of soluble fertilizer components coated with a semipermeable material that allows the soluble fertilizer components to release over an extended period. Assuming adequate substrate moisture, temperature is the primary environmental factor determining the release of nutrient elements from CRF (Birrenkott et al., 2005; Du et al., 2006; Husby et al., 2003). The release rate for a given CRF is the time for a CRF to release 80% to 90% of its nutrients at a specified temperature, typically 16 to 32 °C. Commonly used CRFs in container production have labeled release rates of 4 to 18 months. It follows that production factors that moderate substrate temperatures will also moderate nutrient release rates from CRF.

High substrate temperatures result when black walls of conventional plastic containers absorb direct or reflected solar radiation. Substrate temperatures near the southwest-facing walls of spaced, black plastic containers can exceed 50 °C (Arnold and McDonald, 2006; Martin and Ingram, 1988). Deleterious effects of high container substrate temperatures on plant roots and plant growth have been well documented and include direct root injury (Ingram et al., 2015) and decreased plant growth and development (Mathers, 2003; Nambuthiri et al., 2015a; Ruter, 1993).

The placement of containers in close spacings can limit the solar radiation effect; however, growers would need to move containers one or more times during the season to prevent overcrowding and to maintain plant shape and quality, and this incurs a major labor cost. Million et al. (2007) reported that spacing plants midseason vs. at planting reduced substrate temperatures by 8 to 9 °C during the first month and reduced leaching loss of N by 24% when CRF was incorporated; spacing had no effect when CRF was surface-applied.

Container material can play a significant role in moderating substrate heat. Conventional black polyethylene containers are resistant to degradation in sunlight, and their low cost has made them the industry standard despite their heat-absorbing characteristic. Alternative container colors have been found to reduce the heat effect by reducing solar radiation absorption (Keever and Cobb, 1984; Markham, et al., 2011), but their use has not been widely accepted. An alternative to conventional black plastic containers (PLA) are fabric containers (FAB) made from unwoven, polypropylene or polyester. The porous fabric imparts air-pruning properties that stimulate fibrous root development and minimize undesirable root circling (Privett and Hummel, 1992). The porous fabric also allows for evaporative water loss from side walls that can greatly moderate substrate temperatures. Arnold and McDonald (2006) reported substrate temperatures near the southwest-facing walls of PLA were 19 °C higher (55 vs. 36 °C) than for FAB. Nambuthiri et al. (2015b) found maximum substrate temperatures in PLA were 14 °C higher (42 vs. 28 °C) than for FAB for an August day in Kentucky.

Evaporative water loss from porous container sidewalls adds to the irrigation requirement. Water loss from porous clay containers was approximately twice as much as from plastic containers (Bunt and Kulwiec, 1971). In a multistate evaluation, Wang et al. (2015) reported variable effects of FAB on water use. In Kentucky, water use in FAB was 20% higher than for PLA, whereas in Michigan, water use by FAB was 34% lower. Variable effects of FAB on water use may have been due to differences in weather, plant growth, and/or irrigation regimen. Under controlled environmental conditions, sidewall evaporation from a 3.8-L FAB container was 3.9 mL·h^{-1} (Nambuthiri et al., 2015a). Although some have reported 2- to 3-fold increases in irrigation water use in certain porous containers (Evans and Karcher, 2004), scientific reports comparing FAB to PLA are lacking.

Despite the well-documented effect of FAB on moderating substrate temperatures compared with PLA, to our knowledge, the effect of FAB on nutrient release from CRF has not been investigated. The objective of our experiments was to compare the growth, water use, and leaching losses of N and P when producing a common landscape shrub in PLA vs. FAB. To limit the effect of irrigation, irrigation was adjusted independently for each container type using a leaching fraction (LF) based (LF = container drainage/irrigation applied) schedule. Two experiments were

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conducted with similar methods, but the first was planted in the summer and the second in the spring. Due to much higher leachate volumes for FAB in the first experiment, we adjusted FAB irrigation in the second experiment with the goal of achieving similar leachate volumes as PLA.

Materials and Methods

Two experiments were conducted on the campus of the University of Florida in Gainesville (29.6N, 82.3W). The gently sloped (1% to 2%) site was covered with black, industry-standard black, polypropylene ground cloth. The site's microirrigation system consisted of eight individually controlled irrigation lines. The six interior lines irrigated experimental plants, and the two outside lines irrigated border plants. The six experimental lines were in a randomized block design with two container types (PLA or FAB) and three blocks. Each irrigation line had nine spray-stake assemblies, eight of which were used to irrigate plants (one per container) and one placed in a 15-L pail to collect irrigation water continuously. Each spray-stake assembly included a pressure compensating button (01WPCJ25; Netafim, Tel Aviv, Israel), a 1-m-long section of polyethylene tubing (0.64 cm diameter), and a down-spray emitter (CFd Black; Antelco, Longwood, FL) rated at 23 $L \cdot h^{-1}$ at 103 kPa. Irrigation water collected from each emitter during a 5-min irrigation cycle indicated a high distribution uniformity (DU = 98%) and an average application rate of 319 ± 6 $cm^3 \cdot min^{-1}$. Of the eight containers per line, the outer two served as borders. Of the six interior plants per line, three were used for routine LF testing, and three were used for continuous leachate collection; all six were used to monitor plant growth. Each of the six interior plants per line was placed on an elevated aluminum pizza pan with a drain hole for routine LF testing or continuous leachate collection. We used 33-cm-diameter pans for PLA and 38-cm-diameter pans for FAB; all pans had a straight wall height of 3.8 cm. The 64 containers (eight lines × eight containers) were placed in an equidistant pattern with a container spacing (center-to-center) of 0.91 m (13,800 containers per hectare).

Irrigation was scheduled three times (cycles) per day: 0915, 1315, and 1715 HR. Irrigation was automatically controlled using a programmable logic controller (PLC; D0-DA06; Automation Direct, Atlanta, GA). A weather station (Vantage Pro 2 Plus; Davis Instruments; Hayward, CA) located on-site provided hourly weather data including solar radiation, minimum and maximum temperature, and rain. The PLC was programmed to automatically cancel an irrigation cycle if the amount of rain received after the previous cycle exceeded the scheduled amount of irrigation water to apply.

The daily amount of water to apply was based on LF testing; however, the method of LF testing was different for the two experiments. For Expt. 1, LF tests were conducted once every 2 weeks on three plants per line. LF tests were only conducted on days when weather conditions provided normal evapotranspiration (ET) rates. For LF testing, a pan was placed under the drain hole of the pizza pan to collect leachate over a 24-h period (all three cycles). Except for a small opening for collecting drainage, leachate pans were covered to minimize evaporation of leachate. The amount of irrigation water applied during the same 24-h period was determined by weighing the irrigation collector pail before and after the LF test. The volume of irrigation water applied by each line was used in the calculations for each of the three LF measurements per line. The average LF of the three test containers per line (LF_1) and the run time (RT_1) were used to calculate a new irrigation run time (RT_2) based on a target LF (LF_2) of 25% according to:

$$RT_2 = RT_1 \times (100\% - LF_1)/(100\% - LF_2).$$

The new run time was divided equally between the three cycles. After each test, the new LF-adjusted run time remained constant until the following LF test was conducted.

For Expt. 2, LF testing was conducted daily using small (5 cm × 10 cm), tipping bucket rain gauge sensors (MISOL International E-Commerce; Jiazing, China) placed under pizza-pan drain holes. This tactic was similar to that used by Cypher et al. (2021) who constructed tipping bucket rain gauge systems for measuring leachate volume in container nurseries. The 18 sensors were wired as discreet inputs to the PLC. Just before the first irrigation cycle of the day, the PLC outputted the total number of rain gauge tips. The leachate volume per tip was calculated as the number of tips multiplied by 1.6 mL per tip. On the basis of high leachate volumes for FAB compared with PLA when using the same target LF value of 25% as in Expt. 1, we adjusted PLA irrigation to target a LF of 25% but then adjusted FAB to target the same leachate volume as PLA for Expt. 2. Our goal was to put similar leaching pressure on PLA and FAB knowing FAB was requiring more water.

For continuous leachate collection, leachate from three containers per line was directed into a PVC pipe apparatus that directed the combined leachate into 50-L tubs buried in the ground. Black self-adhesive sports wrap was wrapped around the lower portion of each container to form a "skirt" over the pizza pan to prevent rain from directly entering the leachate collection apparatus. Volumes of leachate and irrigation water were measured weekly by weighing to the nearest 0.01 kg. After weighing, 125-mL leachate samples were taken from each collection tub. A separate 30-mL sample was taken for electrical conductivity (EC) measurement. Leachate samples were filtered and stored at 4 °C until submitted to the University of Florida's Analytical Research Laboratory (https://arl.ifas.ufl.edu) within 2 d of sampling. Leachate samples were analyzed for NO_3-N by EPA Method 353.2 (https://www.epa.gov/sites/default/files/2015-08/documents/method_353-2_1993.pdf), Total Kjeldahl N (TKN) by EPA Method 351.2 (https://www.epa.gov/sites/default/files/2015-08/documents/method_351-2_1993.pdf), and Total P by EPA method 365.1 (https://www.epa.gov/sites/default/files/2015-08/documents/method_365-1_1993.pdf). We report N as the sum of NO_3-N and TKN. Total amounts (milligrams per container) of N and P leached each week were calculated by multiplying leachate N and P concentrations ($mg \cdot L^{-1}$) by the volume of leachate collected (liters per container).

Expt. 1 was planted on 2 July 2020 and Expt. 2 on 25 Mar. 2021. Two Dwarf Burford holly (*Ilex cornuta* 'Burfordii Nana') liner plants (24 per tray) obtained from Hibernia Nursery (Webster, FL) were transplanted into either 36-cm-diameter PLA (Trade #5; 500 Squat Series; Haviland Plastic Products, Haviland, OH) or 36-cm-diameter FAB (Smartpot; High Caliper Growing, Oklahoma City, OK) containers filled with a substrate composed by volume of 70% pine bark, 20% Florida peat, and 10% leaf compost (Oldcastle, Lakeland, FL). The substrate was amended with dolomitic limestone at 4.2 $kg \cdot m^{-3}$ and a micronutrient blend (Micromax; ICL, St. Louis, MO) at 0.89 $kg \cdot m^{-3}$. The volume of substrate in each container was 18 L. Because the bottom diameter of PLA was 30 cm and the FAB 36 cm, the substrate depth was 18 cm in the FAB and 23 cm in the PLA.

To determine the effect of container dimension on substrate physical properties, we lined three containers of each container type with a thin plastic bag and filled with 18 L of substrate. Water was applied intermittently over a 4-h period until saturation was reached. After weighing, six drain holes were punched into the plastic bags, and containers were allowed to drain for 1 h. Containers were weighed again to calculate the volume of drainage water. Percent air space was calculated as the volume of drainage water divided by 18 L. The percent water in wet substrate after draining was determined by drying the substrate in a forced-air oven at 65 °C. Percent water holding capacity (WHC) was calculated as the total volume of water held after drainage (container capacity) divided by 18 L.

A 18N–2.3P–6.6K CRF (Nutricote Total 18–6–8, 270-d release at 25 °C; Florikan, Sarasota, FL) was incorporated at the label-recommended medium rate of 128 g per container (23 g N and 3.4 g P per container). Fertilizer was weighed out for each container to ensure they each received the correct amount. Transplants were uniformly watered-in manually (3.5 L) so as not to result in drainage and containers were set out in the experimental area. Once set out, containers were hand-watered for 2 d before a regular irrigation schedule was started. Plants were initially irrigated 1.5 $L \cdot d^{-1}$ until the first LF test was conducted.

Plant growth was monitored by measuring plant height and plant width at the start and then once every 2 weeks. Plant height was measured from the substrate surface to the uppermost foliage. Plant width was the average of two perpendicular measurements with one parallel to the irrigation pipe. We have found that maintaining the same orientation for size measurements provides more consistent plant growth results. Plant size was the average of plant height and width.

Substrate temperature was monitored with soil temperature sensors (TMC-20-HD; Onset Computer Corp., Bourne, MA) and data loggers (Hobo U4; Onset Computer Corp.). One sensor was inserted 5 cm deep and 3 cm away from the southwest-facing wall of two containers per container type. Temperatures were logged at 30-min intervals, and daily minimum (Tmin), maximum (Tmax), and average (Tavg) temperatures were determined. Substrate temperatures for Expt. 1 were not logged for 4 weeks between 10 Aug. and 11 Sept. 2020.

The last of the 31 weekly leachate collections was made on 31 Dec. 2020 (Expt. 1) and 28 Oct. 2021 (Expt. 2). Weekly volumes of irrigation and leachate were totaled, along with associated amounts of N and P. Volume-weighted concentrations of N and P ($mg \cdot L^{-1}$) were calculated by dividing total amounts leached (mg per container) by the total leachate volume (L per container). Plant canopy growth was the change in plant height and width from the start to the end of the experiment. For Expt. 2 only, shoots were cut at the substrate surface and dried for 48 h at 65 °C to determine shoot dry weight at the end of the experiment. The experiments were analyzed as randomized complete block designs with two container types as treatments and three blocks using the Proc GLM procedure of Statistical Analysis System 9.4 (SAS Institute, Cary, NC). There was one replication per treatment block for irrigation and leachate response variables and six replications per treatment-block for plant response variables. Substrate temperature data were analyzed as a factorial design with container type and week as main factors.

Results

Plant growth. Growth in plant height and width after 31 weeks was unaffected ($P > 0.05$) by container type in Expt. 1 (Table 1). For Expt. 2, growth in plant height was unaffected by container type but FAB increased plant width by 9 ± 7%, plant size by 8 ± 7% (42 vs. 39 cm) and shoot dry weight by 12 ± 6% compared with PLA. The pattern of Dwarf Burford holly canopy growth for the two experiments is compared in Fig. 1. For Expt. 1 planted in July 2020, little shoot growth occurred during the first 6 weeks after planting. The first shoot flush was variable with staggered growth occurring 6 to 10 weeks after planting (13 Aug. to 10 Sept.). A second period of active growth occurred 18 to 22 weeks after planting (5 Nov. to 3 Dec.). Plants remained dormant through the remainder of the experiment. The planting in late Mar. 2021 resulted in greater and more uniform growth for Expt. 2, which was planted in the mild temperatures of late March and was ended in late October before cool-season dormancy began.

Table 1. Impact of fabric (FAB) or conventional black plastic (PLA) containers on dwarf Burford holly growth in 36-cm containers. Expt. 1 was planted on 2 July 2020 and Expt. 2 on 25 Mar. 2021. Initial heights and widths were 28 and 26 cm in Expt. 1 and 23 and 20 cm in Expt. 2. Shoot dry weight (dwt) was not determined in 2020. Means represent the average of 18 plants.

	2020 growth		2021 growth		2021
	Ht	Width	Ht	Width	Shoot dwt
Container	(cm)				(g)
PLA	30	34	38	40	230
FAB	28	36	41	44	257
$LSD_{0.05}$	5	4	5	3	15
Significance	NS	NS	NS	**	**

LSD = least significant difference.

NS, **Nonsignificant or $P > F$ significant at the 0.01 level, respectively.

Substrate physical properties. FAB held 1.0 L of water more (9.9 vs. 8.9 L) at container capacity than PLA, resulting in WHC of 55% and 49%, respectively. Higher WHC in FAB resulted in lower percent air space (19 vs. 29%) compared with PLA. The optimal range of WHC for container substrates is 45% to 65% while the optimal range for air space is 10% to 30% (Bilderback et al., 2005). Despite the observed differences in WHC and air space between FAB and PLA, WHC and air space properties for both container types were within the recommended ranges.

Substrate temperature. FAB containers reduced Tmax and Tavg compared with PLA, but the magnitude of the Tmax effect depended on the week for both experiments (Table 2; Fig. 2); container type had little effect on Tmin. The effect of FAB in reducing Tmax was greater in Expt. 1 than in Expt. 2 (Fig. 2). For Expt. 1, Tmax averaged 8 ± 1 °C cooler in FAB than in PLA (29 vs. 37 °C) but only 4 ± 1 °C cooler (33 vs. 37 °C) in Expt. 2. For Expt. 1, highest maximum daily substrate temperatures of 51 °C and 38 °C were observed for PLA and FAB, respectively, during week 5 (30 July to 5 Aug. 2020). Week 5 experienced high afternoon solar radiation levels (average daily maximum of 910 $W \cdot m^{-2}$) and high maximum air temperatures (average daily maximum of 34 °C). For Expt. 2, highest maximum daily substrate temperatures of 49 and 40 °C were observed for PLA and FAB, respectively, during week 22 (19 Aug. to 25 Aug. 2021). Like

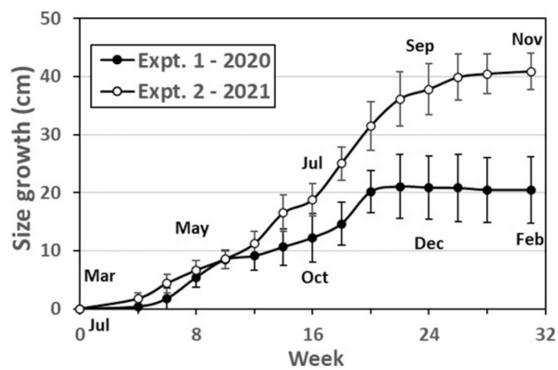

Fig. 1. Comparison of dwarf holly growth in 36-cm-diameter containers for two 31-week experiments. Plant size = (height + width)/2. Expt 1. was planted 2 July 2020 and Expt. 2 on 25 Mar. 2021. Means represent averages of two container types (fabric and plastic) and 18 plants per container type. Error bars are ± SD (n = 36).

Table 2. Minimum (Tmin), maximum (Tmax), and average (Tavg) substrate temperatures measured 3 cm away from the southwest-facing container wall at a depth of 5 cm as affected by conventional black plastic containers (PLA) or fabric containers (FAB). Two 31-week experiments ran from 2 July 2020 to 31 Dec. 2020 (Expt. 1) and from 25 Mar. 2021 to 28 Oct. 2021 (Expt. 2).

	Expt. 1			Expt. 2		
Container	Tmin	Tmax	Tavg	Tmin	Tmax	Tavg
PLA	16.4	37.3	23.3	21.2	35.1	27.6
FAB	16.1	29.2	20.2	20.6	30.8	24.7
$LSD_{0.05}$	0.4	1.0	0.3	0.3	0.7	0.3
Significance						
Week (W)	***	***	***	***	***	***
Container (C)	NS	***	***	***	***	***
W × C	NS	***	NS	NS	***	*

LSD = least significant difference.

NS, *, ***Nonsignificant or $P > F$ significant at the 0.05 or 0.001 levels, respectively.

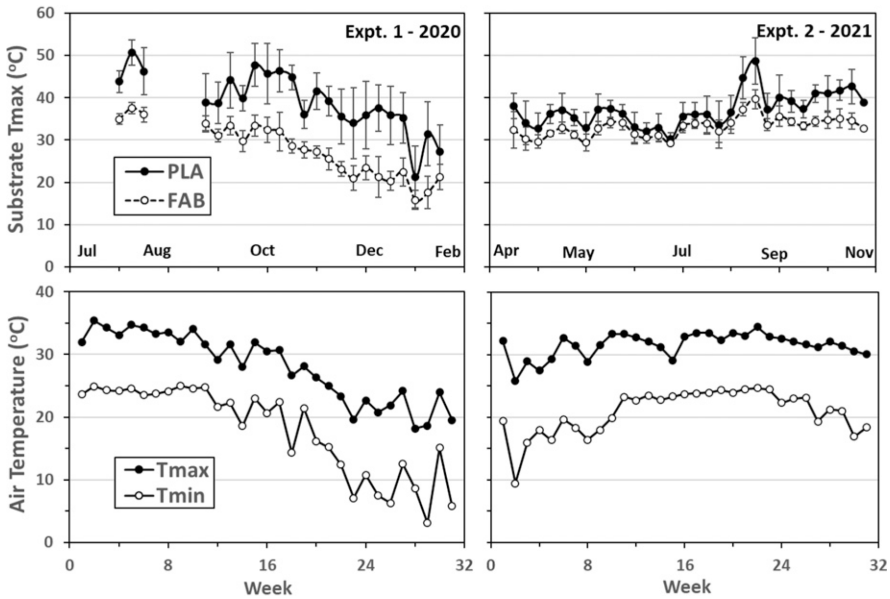

Fig. 2. Maximum daily substrate temperatures measured 3 cm from the southwest-facing edge of the container at a depth of 5 cm. Corresponding air minimum (Tmin) and maximum (Tmax) temperatures were measured on-site. Dwarf Burford holly were grown in 36-cm-diameter black plastic (PLA) or fabric (FAB) containers. Markers represent the average of seven daily values for a given week. Expt. 1 (left) was planted on 2 July 2020 and Expt. 2 (right) on 25 Mar. 2021.

week 5 in Expt. 1, week 22 for Expt. 2 also experienced high afternoon solar radiation levels (average daily maximum of 849 $W \cdot m^{-2}$) and high maximum air temperature (average daily maximum of 34 °C). FAB reduced Tavg by 3.1 ± 0.3 °C (21 vs. 24 °C) in Expt. 1, and 2.9 ± 0.3 °C (25 vs. 28 °C), respectively, for Expt. 2.

Irrigation water applied and leachate volume. Routine LF testing was conducted to adjust irrigation to a target LF of 25%. Routine LF tests averaged 29% and 28% for PLA and FAB, respectively, for Expt. 1 (17 LF tests), and 25% and 18% for PLA and FAB, respectively, for Expt. 2. Because LF tests for Expt. 2 were essentially conducted daily using rain gauge sensors, LF results in Expt. 2 were averages of all days unaffected by rainfall. Lower LF values for FAB compared with PLA in Expt. 2 resulted from our strategy to adjust FAB irrigation to achieve similar leaching volumes as PLA, which was adjusted to a target LF of 25%.

Total volume of irrigation water applied was 81% (Expt. 1) and 56% (Expt. 2) greater for FAB vs. PLA, respectively (Table 3). The pattern of irrigation water applied was different for each experiment (Fig. 3). For Expt. 1, higher amounts of water were applied toward the beginning of the experiment in the summer and then tapered off in the winter. For Expt. 2, applied amounts of water for both container types remained high throughout the experiment resulting in total amounts that were 34% greater (336 vs. 250 L/container) than in Expt. 1. For Expt. 1, the average weekly volume of applied irrigation water ranged from 4 to 8 L per container per week for PLA and from 6 to 16 L per container per week for FAB. For Expt. 2, the average weekly volume of applied irrigation water ranged from 4 to 12 L per container per week for PLA and from 8 to 16 L per container per week for FAB. Especially for Expt. 2, irrigation was reduced during the rainy summer months.

Table 3. Impact of fabric (FAB) or conventional black plastic (PLA) containers on irrigation water applied and leachate loss of N and P. Leachate was continuously collected and sampled weekly during 31 weeks of production of Dwarf Burford holly in 36-cm containers at a density of 13,800 containers per hectare. Expt. 1 was planted on 2 July 2020 and Expt. 2 on 25 Mar. 2021. Preplant incorporated, controlled-release fertilizer supplied 23 g of N and 3.4 g of P per container.

				Leachate loss (g/container)	
Expt.	Container type	Irrigation water (L/container)	Leachate (L/container)	N	P
1	PLA	178	132	10.3	1.18
	FAB	322	194	6.4	0.57
	$LSD_{0.05}$	25	35	1.7	0.38
	Significance[z]	**	*	**	*
2	PLA	263	207	6.3	1.14
	FAB	409	249	5.0	0.67
	$LSD_{0.05}$	46	21	0.6	0.20
	Significance	**	*	*	**

LSD = least significant difference.

*, ***P* > F significant at the 0.05 or 0.01 levels, respectively.

Total volume of leachate collected was 47% (Expt. 1) and 20% (Expt. 2) greater for FAB than for PLA (Table 3). Weekly leachate volumes varied greatly for both experiments depending largely on weekly rainfall (Fig. 4). Total rainfall was 59 and 101 cm for Expt. 1 and Expt. 2, respectively. Assuming no plant effect on rain capture and a container top area of 1018 cm^2, these rain totals were estimated to contribute 60 and 103 L of additional water per container for Expt. 1 and Expt. 2, respectively. These contributions from rainfall equal 34% and 19% of the irrigation water applied to PLA and FAB, respectively, in Expt. 1, and 39% and 25% of the irrigation water applied to PLA and FAB, respectively, in Expt. 2.

Nutrient leaching. FAB reduced total leachate losses of N and P compared with PLA (Table 3). FAB reduced total leachate N loss by 38% in Expt. 1 and by 21% in Expt. 2. Nitrate-N comprised 98% and 95% of N for PLA and FAB, respectively, in Expt. 1, and 90% and 86%, respectively, in Expt. 2. FAB reduced total leachate P loss by 52% in Expt. 1 and by 41% in Expt. 2. In terms of the 23 g of N applied in the fertilizer, FAB reduced the percent of applied N that was lost in leachate from 44% to 27% in Expt. 1 and from 27% to 22% in Expt. 2. In terms of the 3.4 g of P applied in the fertilizer, FAB reduced the percent of applied P that was lost in leachate from 35% to 17% in Expt. 1 and from 34% to 20% in Expt. 2. Concentrations of N and P in irrigation water were 0.12 and $<0.001\ mg \cdot L^{-1}$, respectively, so that irrigation water contributed insignificant amounts of N and P relative to the amounts of N and P supplied by fertilizers.

The patterns of leachate loss of N and P given in Fig. 5 indicate the uniformity of release of N and P from CRF as well as the periods of maximum potential environmental impact. For Expt. 1, leachate loss of N and P peaked at 6 to 9 weeks after planting (7 Aug. to 3 Sept. 2020). Leachate N loss for this 4-week period was 48% and 45% of total leachate N loss for PLA and FAB, respectively. Maximum leachate N loss occurred during week 8. For week 8, leachate N loss was 1.5 and 0.8 g representing 15% and 13% of total leachate N loss for PLA and FAB, respectively. Leachate P loss for the same 4-week period was 33% and 31% of total leachate P loss for PLA and FAB, respectively. Maximum leachate P loss occurred during week 8. For week 8, leachate P loss was 0.12 and 0.06 g or 10% and 11% of total leachate P loss for PLA and FAB, respectively.

The pattern of nutrient loss for Expt. 2 showed that leachate loss of N and P peaked 11 to 15 weeks after planting (3 June to 8 July 2021). Leachate N loss for this 5-week period was 50% and 51% of total leachate N loss for PLA and FAB, respectively. Maximum leachate N loss occurred during week 11. For week 11, leachate N loss was 1.6 and 0.9 g representing 26% and 18% of total leachate N loss for PLA and FAB, respectively. Leachate P loss for this 5-week period was 43% and 41% of total leachate P loss for

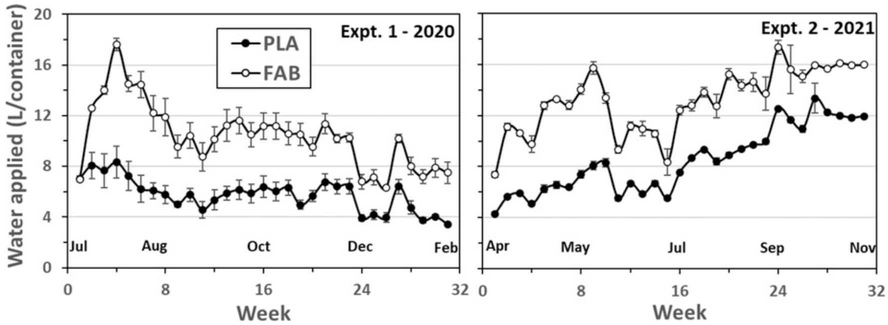

Fig. 3. Weekly volume of irrigation water applied to dwarf Burford holly in 36-cm-diameter conventional plastic (PLA) or fabric (FAB) containers. Expt. 1 (left) was planted on 2 July 2020 and Expt. 2 (right) on 25 Mar. 2021. Microirrigation was adjusted to a target leachate fraction of 25%. In Expt. 2, irrigation of FAB was adjusted to provide a similar volume of leachate as PLA containers. Error bars are ± SD (n = 3).

PLA and FAB, respectively. Maximum leachate P loss occurred during week 15. For week 15, leachate P loss was 0.16 g and 0.11 g or 14% and 16% of total leachate P loss for PLA and FAB, respectively.

Higher leachate N and P concentrations were observed in Expt. 1 than in Expt. 2 (Fig. 6). For Expt. 1, leachate N concentrations for PLA during weeks 4 through 9 (24 July to 3 Sept. 2020) were >100 mg·L^{-1} with a maximum N concentration of 225 mg·L^{-1} observed for week 7. During that same 6-week period, leachate N concentration for FAB ranged from 37 to 80 mg·L^{-1} with the highest N concentration also observed for week 7. Leachate P concentrations for PLA were >8 mg·L^{-1} from week 3 to week 20 with a maximum P concentration of 14 mg·L^{-1} observed for week 7. During that same period, leachate P concentrations for FAB were much less, ranging from 2.0 to 4.3 mg·L^{-1} with the highest P concentration observed for week 8.

For Expt. 2, leachate N concentrations were lower and more variable week to week. Maximum leachate N concentrations for both container types were observed for week 11. For week 11, leachate N concentrations were 148 and 66 mg·L^{-1} for PLA and FAB, respectively. Highest leachate P concentrations (>6 mg·L^{-1}) for PLA were observed from week 11 to week 14 with a maximum leachate P concentration of 9.5 mg·L^{-1} observed for week 14. Compared with PLA, FAB P concentrations were more uniform throughout Expt. 2, with values generally between 2 and 4 mg·L^{-1}.

Volume-weighted concentrations of N and P for our experiments represent the net concentration of N and P that drained out of containers and could impact surrounding natural water bodies and nearby well water. Volume-weighted N concentrations for PLA and FAB were 76 and 32 mg·L^{-1}, respectively, for Expt. 1 and 30 and 20 mg·L^{-1}, respectively, for Expt. 2. Volume-weighted P concentrations for PLA and FAB were 9.0 and 2.9 mg·L^{-1}, respectively, for Expt. 1, and 5.5 and 2.7 mg·L^{-1}, respectively, for Expt. 2.

Leachate EC was a good indicator of leachate N concentration (Fig. 6). The exception was for the first two weekly leachate collections for both container types and for both experiments. Particularly for the first of the two leachate collections, EC values indicated much higher N values than for the rest of the leachate collections. We suspect this was due to the leaching of salts other than fertilizer salts that may have accumulated in the substrate before planting. Disregarding the first two weekly leachate collection outliers, the relationship between leachate EC (dS·m^{-1}) and leachate N concentration (mg·L^{-1}) for both container types and for both experiments (n = 372) was N = 111EC – 45; R^2 = 0.83.

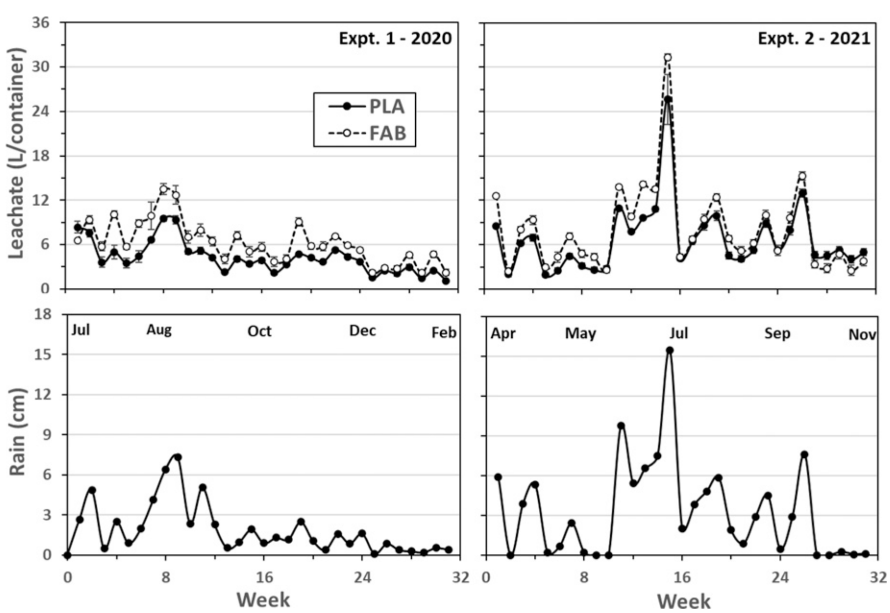

Fig. 4. Weekly leachate volume and rain during production of Dwarf Burford holly in 36-cm-diameter conventional black plastic (PLA) or fabric (FAB) containers. Leachate was collected continuously and sampled weekly. Expt. 1 (left) was planted on 2 July 2020 and Expt. 2 (right) on 25 Mar. 2021. Error bars are ± SD (n = 3).

Discussion

The primary objective of the experiment was to determine whether FAB's effect on reducing substrate temperature would also reduce the leachate loss of N and P supplied by CRF. By monitoring substrate temperatures, we found that, compared with PLA, FAB reduced Tavg 3 °C in both Expt. 1 and Expt. 2. The cooling effect of FAB on Tavg was primarily due to reducing Tmax, as Tmin was little affected by container type. Compared with PLA, FAB reduced Tmax an average 8 °C and 4 °C in Expt. 1 and Expt. 2, respectively. Nambuthiri et al. (2015b) reported PLA had an average substrate temperature that was 6 °C higher than for FAB. Tauer and Cole (2009) reported no substrate temperature difference between the two container types when measured in the center of the containers. In Expt. 2, we found little difference (<1 °C) in substrate temperatures near the center of the containers compared with the significant temperature differences measured near the container edge (limited data not shown). Regarding potential effect of substrate temperature on CRF release rate, it is likely that the cooling effect of FAB on the overall average substrate temperature of the entire substrate volume was somewhere between the 6 °C difference measured at the container's edge and the minimal difference measured near the center of the container.

The greater cooling effect of FAB in Expt. 1 may have been due to several factors. One was the reduced growth of Dwarf Burford holly plants in Expt. 1 when planted in July compared with the March planting for Expt. 2. Smaller plants provided less shading and lower transpiration rates resulting in greater sidewall evaporation and, therefore, greater substrate cooling. A second difference was the greater and more consistent rains that occurred in Expt. 2. Third, the irrigation schedule for FAB in Expt. 2 was not adjusted to a target of 25% but adjusted to equal the leachate volume of PLA. This strategy resulted in an average LF of 18% for FAB in Expt. 2 compared with an average LF of 29% in Expt. 1. Higher irrigation rates in Expt. 1 likely led

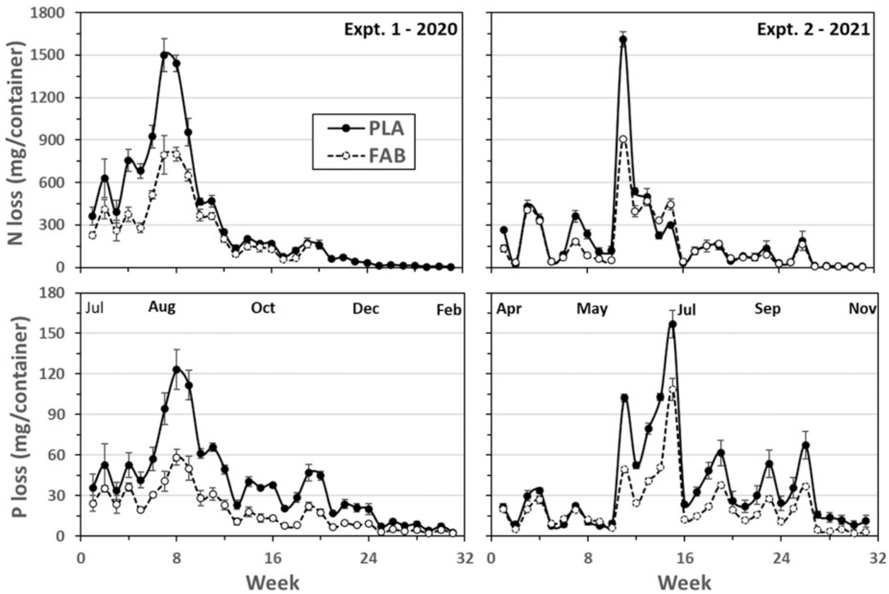

Fig. 5. Weekly leachate loss of N and P during production of Burford holly in 36-cm-diameter conventional black plastic (PLA) or fabric (FAB) containers. Leachate was collected continuously and sampled weekly. Expt. 1 (left) was planted on 2 July 2020 and Expt. 2 (right) on 25 Mar. 2021. Error bars are ± SD (n = 3).

to higher moisture contents, in turn leading to higher sidewall evaporation rates and thus a greater cooling effect. Regardless, the premise that FAB can reduce substrate temperatures even with three cycles of microirrigation was confirmed in our two experiments.

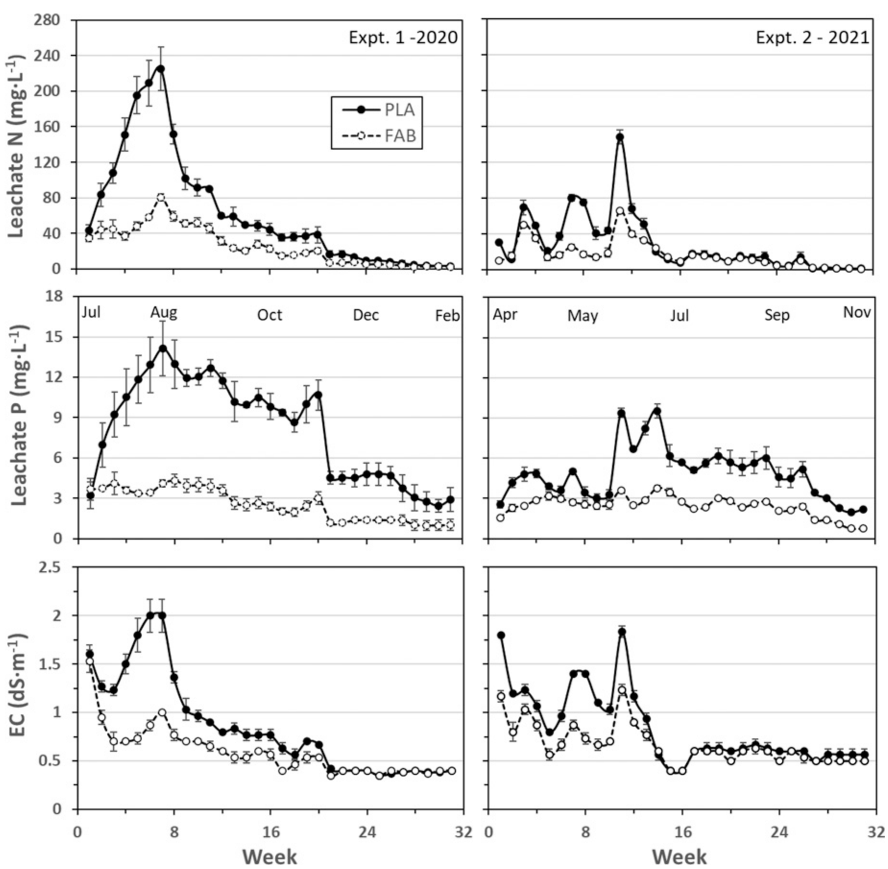

Fig. 6. Weekly leachate N and P concentration and electrical conductivity (EC) during production of Burford holly in 36-cm-diameter conventional black plastic (PLA) or fabric (FAB) containers. Leachate was collected continuously and sampled weekly. Irrigation water EC was 0.3 dS·m^{-1}. Expt. 1 (left) was planted on 2 July 2020 and Expt. 2 (right) on 25 Mar. 2021. Error bars are ± SD (n = 3).

FAB reduced the leaching loss of applied N and P in both experiments despite an increase in irrigation water applied and an increase in volume of leachate collected. In Expt. 1, FAB reduced leachate N loss by 38% and P loss by 52% despite applying 81% more irrigation water and collecting 47% more leachate. In Expt. 2, FAB reduced N loss by 21% and P loss by 41% despite applying 56% more irrigation water and collecting 20% more leachate. Although these results support the contention that lower substrate temperatures in FAB reduced N and P release rates from CRF prills, we were surprised to observe that CRF longevity did not seem to be greatly affected, particularly for N. In both experiments, by week 16 leachate N loss was similar for the two container types. If leachate N loss during the first 15 weeks was lower for FAB, we were expecting greater leachate N loss (i.e., greater CRF longevity) for FAB later in the experiments. By week 24, leachate N concentrations remained constantly low (<10 mg·L^{-1}) for both container types indicating that most of the CRF N had been released. For both container types in Expt. 1, 99% of total leachate N loss for the 31-month experiment had occurred by week 24. In Expt. 2, 96% and 95% of total leachate N loss for PLA and FAB, respectively, had occurred by week 24. Because CRF longevity did not seem to be greatly affected, we wondered if some other mechanism may have reduced leachate N loss in FAB. We observed that the lower height of FAB due to its straight wall design resulted in higher substrate moisture levels at lower substrate depths than for PLA. Denitrification rate increases under anaerobic conditions caused by saturated substrate moisture conditions (Barton et al., 1999) and may have contributed to greater gaseous loss of N in FAB through this mechanism. Pitton et al. (2022) attributed unaccounted loss of fertilizer N (28%) to denitrification. Although visually not apparent, increased plant N uptake in FAB may have also contributed to the observed lack of difference in leachate N loss during the last 2 months of the experiments. Another contributing factor may have been that the well-developed root systems efficiently "scavenged" CRF-released N toward the end of the experiments so that leachate N levels remained low. We did not measure plant N uptake, but in Expt. 2, a 10% increase in shoot weight for FAB may have accounted for some potential increase in N release from CRF in FAB toward the end of the experiment. Another potential but unknown factor that might have affected leachate N loss may be the sideward movement of nongravitational water toward FAB container walls due to sidewall evaporation.

Although the use of FAB for aboveground plant production will primarily be for FAB's root pruning properties, this research provides evidence that FAB may have added benefits of reducing environmental impacts of nutrient loss from fertilized container substrates. The 1972 Federal Clean Water Act mandated that states implement Total Maximum Daily Load (TDML) programs for all watersheds to address point and non-point sources of pollution including N and P (Lea-Cox and Ross, 2001).

Basin Management Action Plans (BMAP) are being developed to meet TDML goals and the role of agricultural producers in BMAP is being increasingly evaluated (Boman and Obreza, 2010). This research showed that FAB reduced nutrient loading, albeit at the added cost of requiring more irrigation water to offset sidewall evaporation. In our two 31-week experiments, FAB reduced average N load from 114 to 78 $kg \cdot ha^{-1}$ and average P load from 16.0 to 8.6 $kg \cdot ha^{-1}$. These results indicate the importance of developing new management strategies such as the use of FAB that can reduce leachate losses of N and P in container nurseries.

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