Recycled Paper as a Growth Substrate for Container *Spiraea* Production

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Abstract. *Spiraea japonica* L. f. 'Froebelii' were grown in 3.8-L containers filled with substrates consisting of recycled paper (RP) and pine bark at rates of 0%, 25%, 50%, 75%, or 100% (by volume) RP. Fertilizer treatments included 100% of the recommended rate of N as controlled release (CRF) or liquid fertilizer (LF) or both. The same amounts of N (as NO_3^- -N and NH_4^+ -N), P and K were supplied with each fertilizer treatment. Plants were irrigated in Fall 1996 based on substrate water-holding capacity and to achieve a 25% to 50% leaching fraction. In Spring 1997 regardless of substrate water holding capacity, plants were irrigated weekly initially, then twice weekly later in the study when plants were larger. Fertilizer treatment did not affect plant size, but plant diameter and shoot and root dry weight decreased as substrate RP concentration increased in Fall 1996. All plant size parameters measured decreased as substrate RP concentration increased regardless of fertilizer treatment in Spring 1997. In Fall 1996, shoot and root N concentration increased as CRF decreased (and LF increased), but substrate RP concentration did not affect shoot or root N concentration. In Spring 1997, shoot and root N concentration generally decreased as substrate RP concentration increased with 50% CRF, 50% LF, or 100% LF. Leachate NO_3^- -N, NH_4^+ -N and total N generally increased as CRF decreased but decreased as substrate RP concentration increased in both years. Substrate volume and percentage of air space decreased, but bulk density increased, as RP concentration increased. Although N leaching decreased as substrate RP concentration increased in both years, reasonable plant growth occurred only in those substrates containing $\leq 50\%$ RP.

Several nontraditional organic and inorganic materials have been tested as container growth substrates, including coir (Meerow, 1994), spent mushroom compost (Chong et al., 1987), kenaf stem core (Wang, 1994), and ground automobile tires (Bowman et al., 1994; Jarvis et al., 1996). In similar studies, nonrecyclable waste papers, such as food-contaminated papers, wax-coated corrugated cardboard (Chong, 1995; Cole and Newell, 1996; Raymond et al., 1999), and papermill wastes (Adamson and Maas, 1971; Chong and Cline, 1993; Lumis, 1976; Tripepi et al., 1996), have been tested. Interest in these substrates arises from concerns over current use of slowly renewable resources, such as peat, and the desire to recycle waste materials. Adoption by

container plant producers of alternative substrates that recycle waste materials could reduce both depletion of natural resources and the amount of waste entering landfill sites.

To be considered a viable component of container-plant substrates, a material must be well-drained, and have adequate air space, water-holding capacity and resistance to shrinkage and compaction. The ideal container substrate has 20% to 30% air space and 70% to 85% total pore space (Bunt, 1988). Substrate pH, salts, cation exchange capacity (CEC), and nutrient levels should also be within established ranges for the species grown.

Containers limit water and nutrient availability to the plants, and container plant producers tend to irrigate and fertilize their crops heavily. These practices can lead to leaching of nutrient ions, causing environmental pollution. The use of substrate components with a high CEC to provide maximum retention of positively charged nutrient ions is desirable (Dole and Wilkins, 1999). Further, to assure adequate nutrient availability for plant growth, pH of container mixes is generally lower (5.0–6.5) than that of field soils (6.5–7.0) (Warnecke, 1990).

Objectives of this research were to determine the influence on plant growth and N leaching of substrates containing various ratios of recycled paper (RP) and pine bark (PB) under three fertilizer treatments, and to characterize the change in physical and chemi-

cal properties of the substrates from initiation to completion of the experiment. The RP used in this research was Wet Earth® (CERAD, Sand Springs, Okla.), a patented product consisting of 80% recycled paper, 18% diatomaceous earth, 1% CaO, and 1% humic acid by volume. The RP used as a base for this product was sludge from the manufacture of tissue paper. The mean particle size of Wet Earth® is 500 μm , and it has a greater surface area than comparable products on the market (Harold Manning, personal communication).

Materials and Methods

Plant material and growing conditions. On 14 Aug. 1996, rooted cuttings of *Spiraea japonica* 'Froebelii', ≈ 12 cm tall, were potted into 3.8-L containers filled with 2300 cm^3 of substrate consisting of RP and PB and containing 0%, 25%, 50%, 75%, or 100% (by volume) RP. Plants were grown in a polyethylene-covered greenhouse under a long photoperiod obtained by a 3-h night interruption with supplemental incandescent lighting (2300 to 0200 HR). The maximum photosynthetic photon flux (PPF) was 924 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ at the plant apex. Air temperatures averaged 32.5 °C day/15.5 °C night.

Fertilization. All substrates were amended with gypsum and Micromax® (The Scotts Co., Marysville, Ohio) at rates of 1.74 and 0.65 $\text{mg}\cdot\text{cm}^{-3}$, respectively. The same amounts of N (as NO_3^- -N and NH_4^+ -N), P, and K were supplied in each fertilizer treatment. In the 100% CRF treatment, 5.2 $\text{mg}\cdot\text{cm}^{-3}$ of 14N–6.2P–11.6K (Osmocote®; The Scotts Co.) was incorporated into each substrate at planting. Because recycled paper has a greater water-holding capacity than does pine bark, irrigation and consequently fertilization varied by substrate in order to maintain the same leaching fraction from all substrates throughout the study. In the 50% CRF, 50% LF treatment, 2.6 $\text{mg}\cdot\text{cm}^{-3}$ of 14N–6.2P–11.6K, 0.4 $\text{mg}\cdot\text{cm}^{-3}$ of 0N–19.8P–0K [triple superphosphate (TSP)], and 0.79 $\text{mg}\cdot\text{cm}^{-3}$ of controlled-release of 0N–0P–39K (K_2SO_4 ; Polyon®, Purcell Ind., Sylacauga, Ala.) were incorporated into each substrate at planting. Ammonium nitrate and $(\text{NH}_4)_2\text{HPO}_4$ were then applied to the various substrates during irrigation at the following concentrations ($\text{mg}\cdot\text{L}^{-1}$), respectively: 0% RP – 367 and 122; 25% RP – 390 and 130; 50% RP – 440 and 146; 75% RP – 504 and 168; and 100% RP – 702 and 234. For the 100% LF treatment, 0.8 $\text{mg}\cdot\text{cm}^{-3}$ of 0N–19.8P–0K and 1.58 $\text{mg}\cdot\text{cm}^{-3}$ controlled-release of 0N–0P–39K were incorporated into each substrate at planting, and NH_4NO_3 and $(\text{NH}_4)_2\text{HPO}_4$ were applied to the substrates during irrigation at the following concentrations ($\text{mg}\cdot\text{L}^{-1}$), respectively: 0% RP – 733 and 244; 25% RP – 781 and 260; 50% RP – 880 and 293; 75% RP – 1008 and 336; and 100% RP – 1404 and 468.

Irrigation. All plants within a substrate treatment were irrigated when a previously selected test plant reached a target irrigation weight. Target weight was determined by planting six extra plants per substrate as de-

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scribed above. Extra plants were irrigated to container capacity and allowed to dry to the permanent wilting point. The weight of container with substrate and plant was recorded. Plants were again irrigated to container capacity and weighed. Target irrigation weight was calculated as [(0.50) (container capacity weight – wilting point weight)] + wilting point weight = container weight at 50% capacity. The time to permanent wilting point was used to estimate the number of irrigations and application rates of LF over the 16-week duration of the experiment. Plants were irrigated with adequate water to provide a 25% to 50% leaching fraction in all substrates.

Because RP has a greater water-holding capacity than does PB, fewer irrigations with more water per irrigation were used to maintain similar leaching fractions as the proportion of RP in the substrate increased. All plants in a given substrate received the same volume of water at each irrigation. However, the substrates received volumes of water at each irrigation averaging 450, 469, 469, 504, and 522 mL/pot for 0%, 25%, 50%, 75%, and 100% RP, respectively. These volumes were determined by the initial water-holding capacity of each substrate. Plants in LF treatments were leached with tap water (no fertilizer) every fourth irrigation.

Analysis of leachate. Containers were nested in plastic funnels seated in the benches when irrigated. Otherwise, containers were spaced 20 × 30 cm on the bench. All leachate was collected in 500 mL graduated cylinders placed beneath each funnel and volumes were recorded. Tap water samples were also taken at each irrigation. A 100-mL aliquot of each leachate sample was filtered, and analyzed by colorimetric methods (cadmium reduction for NO_3^- -N and indolephenol blue for NH_4^+ -N), using a continuous-flow analyzer (Lachat Instruments, Milwaukee; Soil Water and Forage Laboratory, Oklahoma State Univ., Stillwater). The remainder of each sample was analyzed for pH (pH meter 5943-40; Cole-Parmer, Chicago) and electrical conductivity (EC) (Solubridge SD-B15; Beckman Instruments, Cedar Grove, N.J.).

Data recorded. Shoot height and plant diameter (an average of two perpendicular measurements) were measured at planting and monthly thereafter. At planting, and at harvest 4 months later, five plants per treatment were separated into roots and shoots, washed to remove all substrate, fertilizer and pesticide, then dried at 67 °C for 10 d and weighed. All root and shoot samples were ground to pass through a 917- μm mesh screen and analyzed for total N by the macro-Kjeldahl method (Horowitz, 1980).

Growth substrate bulk density, percentage of porosity and percentage of air space were determined at planting and harvest (Ingram et al., 1990). The CEC of each substrate was determined at the Research and Extension Analytical Laboratory, Wooster, Ohio.

Statistical analysis. Five replicates of each treatment were arranged in a split-plot design

with fertilizer as the main plot and growth substrate as the subplot. Analysis of variance and trend analyses were performed using GLM in SAS/STAT (SAS Institute, Cary, N.C.).

1997. Procedures used in 1997 were similar to those used in 1996, with the following exceptions. Dormant, rooted cuttings, ≈ 12 cm tall, were planted 25 Feb. 1997 and grown at air temperatures averaging 33 °C day/12 °C night, and a maximum PPF of 1010 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. Plants were irrigated weekly until mid-April, then twice weekly for the remainder of the study with 500 mL water regardless of substrate. The concentration ($\text{mg}\cdot\text{L}^{-1}$) of NH_4NO_3 and $(\text{NH}_4)_2\text{HPO}_4$ applied at each irrigation was 612 and 204, respectively, in the 50% CRF, 50% LF fertilizer treatment, and 1224 and 408, respectively, in the 100% LF treatment.

Results

Plant growth. In 1996, no fertilizer × substrate interactions were significant for any of the growth parameters measured or for shoot or root N concentration. Plant height, diameter, and root and shoot dry weight were not affected by fertilizer treatment, nor did RP treatment affect plant height or shoot or root N concentration (data not shown). Plant diameter and shoot dry weight decreased curvilinearly, while root dry weight decreased linearly, as substrate RP concentration increased (Table 1). Shoot N concentration decreased linearly, whereas root N concentration increased curvilinearly, as the amount of CRF applied decreased (Table 2).

In 1997, fertilizer treatment did not affect plant height or shoot dry weight, nor were fertilizer by substrate interactions significant (data not shown). Plant height decreased linearly as RP concentration increased, ranging from 38.1 cm (0% RP) to 21.2 cm (100% RP). Shoot dry weight also decreased linearly as substrate RP concentration increased, falling from 17.4 g (no RP) to 2.3 g (100% RP).

Fertilizer × substrate interactions were significant for plant diameter and root dry weight in 1997 (Fig. 1). Plant diameter decreased curvilinearly in the 100% CRF treatment, but linearly in the 50% CRF, 50% LF and 100% LF treatments as substrate RP concentration increased. Root dry weight decreased linearly in the 100% CRF treatment, but curvilinearly in the 50% CRF, 50% LF treatment and in the 100% LF treatment as substrate RP concentration increased.

In 1997, shoot N concentration was not affected with 100% CRF, but decreased linearly with 50% CRF, 50% LF, and curvilinearly with 100% LF as substrate RP concentration increased (Fig. 2). Root N concentration increased linearly with 100% CRF, decreased linearly with 50% CRF, 50% LF, and decreased curvilinearly with 100% LF as substrate RP concentration increased (Fig. 2).

Analysis of leachate. In 1996, substrate by fertilizer interactions for initial and final pH

Table 1. Effects of proportion of recycled paper (RP) to pine bark in substrate on diameter and root and shoot dry weight at harvest of *Spiraea japonica* 'Froebelii' in 1996. n = 15.

Proportion of RP (%)	Plant diam (cm)	Dry wt (g)	
		Shoot	Root
0	35.4	6.6	5.2
25	42.4	7.2	5.0
50	41.3	4.6	4.5
75	29.8	6.0	4.1
100	18.5	3.4	2.3
Linear	***	***	***
Quadratic	***	***	NS

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

Table 2. Effect of fertilizer ratio on N concentration in shoots and roots of *Spiraea japonica* 'Froebelii' in 1996. n = 25.

Fertilizer ratio (controlled release : liquid)	N (% dry wt)	
	Shoot	Root
1:0	4.2	2.9
1:1	3.9	2.8
0:1	3.8	3.4
Linear	**	NS
Quadratic	NS	**

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

and initial EC were significant. A curvilinear relationship existed between initial pH and substrate RP concentration regardless of fertilizer treatment. With 100% CRF, initial pH was highest (6.0) with 25% and 50% RP and lowest (4.4) with no RP. With 50% CRF, 50% LF, initial pH was highest (5.8) with 25% RP and lowest (4.9) with no RP, while with 100% LF, initial pH was highest (5.9) with no RP and lowest (4.2) with 75% RP. At harvest, leachate pH and substrate RP concentration were curvilinearly related with 100% CRF and 50% CRF, 50% LF, but linearly related with 100% LF. With 100% CRF, final leachate pH was highest (6.6) with 75% RP and lowest (4.5) with 100% RP. When 50% CRF and 50% LF were applied, pH was highest (6.7) with 100% RP and lowest (5.5) with 75% RP. With 100% LF final leachate pH was highest (6.5) with 100% RP and lowest (5.2) with no RP. Initial leachate EC was curvilinearly related to substrate RP concentration regardless of fertilizer application. With 100% CRF, initial leachate EC was highest (2.4 $\text{dS}\cdot\text{m}^{-1}$) with 100% RP and lowest (1.4 $\text{dS}\cdot\text{m}^{-1}$) with 25% RP. When 50% CRF and 50% LF were used, initial leachate EC was highest (3.0 $\text{dS}\cdot\text{m}^{-1}$) with 100% RP and lowest (1.5 $\text{dS}\cdot\text{m}^{-1}$) with 25% RP. With 100% LF, initial leachate EC was highest (3.1 $\text{dS}\cdot\text{m}^{-1}$) with 100% RP and lowest (1.4 $\text{dS}\cdot\text{m}^{-1}$) with no RP.

In 1996, no substrate × fertilizer interactions were significant for EC, NO_3^- -N, NH_4^+ -N, or total N in the leachate at harvest (Table 3). All decreased linearly as the amount of CRF applied increased. Final EC increased linearly, whereas leachate NO_3^- -N, NH_4^+ -N and total N concentrations decreased linearly as percentage of RP increased.

In 1997, fertilizer × substrate interactions were significant for initial and final leachate

Fig. 1. (A) Plant diameter and (B) root dry weight at harvest of *Spiraea japonica* 'Froebelii' grown in substrates consisting of various proportions of recycled paper (to pine bark) and receiving 100% controlled-release fertilizer (1:0), 50% controlled-release fertilizer and 50% liquid fertilizer (1:1), or 100% liquid fertilizer (0:1) in 1997; $n = 5$. Regression equations for plant diameter: 1:0, $y = 50.80 + 0.36x - (7.2 \cdot 10^{-3})x^2$; 1:1, $y = 61.58 - 0.32x$; 0:1, $y = 60.22 - 0.38x$. Regression equations for root dry weight: 1:0, $y = 4.68 - (3.08 \cdot 10^{-3})x$; 1:1, $y = 7.42 - 0.11x + (5.26 \cdot 10^{-4})x^2$; 0:1, $y = 8.09 - 0.16x + (9.37 \cdot 10^{-4})x^2$.

Fig. 2. (A) Shoot and (B) root N concentration at harvest of *Spiraea japonica* 'Froebelii' grown in substrates consisting of various proportions of recycled paper to pine bark and receiving 100% controlled-release fertilizer (1:0), 50% controlled-release fertilizer and 50% liquid fertilizer (1:1), or 100% liquid fertilizer (0:1) in 1997; $n = 5$. Regression equations for shoot N concentration: 1:0, nonsignificant; 1:1, $y = 3.08 - (6.80 \cdot 10^{-3})x$; 0:1, $y = 3.06 - (1.64 \cdot 10^{-2})x + (8.00 \cdot 10^{-5})x^2$. Regression equations for root N concentration: 1:0, $y = 1.92 + (9.00 \cdot 10^{-3})x - (4.00 \cdot 10^{-5})x^2$; 1:1, $y = 2.76 - (6.80 \cdot 10^{-3})x$; 0:1, $y = 2.89 - (2.47 \cdot 10^{-3})x + (1.71 \cdot 10^{-4})x^2$.

Table 3. Main effects of method of fertilization and proportion of recycled paper (RP) to pine bark in medium on final electrical conductivity (EC) and amount of NO_3^- -N, NH_4^+ -N, and total N of leachate from *Spiraea japonica* 'Froebelii' in 1996. $n = 5$.

Treatment	Final EC	Leachate N (g)		
	(dS·m ⁻¹)	NO ₃ ⁻ -N	NH ₄ ⁺ -N	Total
<i>Fertilizer ratio (controlled release: liquid)</i>				
1:0	2.0	0.28	0.28	0.56
1:1	2.4	0.40	0.41	0.81
0:1	2.8	0.42	0.48	0.91
Linear	***	**	***	***
<i>RP (%)</i>				
0	1.9	0.61	0.58	1.19
25	2.2	0.43	0.41	0.84
50	2.3	0.33	0.40	0.73
75	2.6	0.30	0.29	0.59
100	3.2	0.17	0.27	0.43
Linear	***	***	***	***

NS, *** Nonsignificant or significant at 0.1%.

pH and EC (Fig. 3). Initial leachate pH was curvilinearly related to RP concentration regardless of fertilizer applied. With 100% CRF, initial pH was highest (5.0) with 75% RP and lowest (4.0) with no RP. When 50% CRF and 50% LF were applied, pH was highest (5.2) with 25% RP and lowest (3.8) with no RP. With 100% LF, pH was highest (4.6) with 50% RP and lowest (3.9) with no RP and 25% RP. Leachate pH at harvest decreased linearly as substrate RP concentration increased with 100% CRF, but there were no trends between pH and substrate RP concentration with 50% CRF, 50% LF or 100% LF. Initial leachate EC increased curvilinearly with 100% CRF, but linearly with 50% CRF, 50% LF and 100% LF as substrate RP concentration increased. Leachate EC at harvest increased linearly with 100% CRF, was curvilinearly related with 50% CRF, 50% LF, and showed no significant trends with 100% LF as substrate RP concentration increased.

In 1997, fertilizer interacted with substrate for the amount of NO_3^- -N, NH_4^+ -N, and total N leached (Fig. 4). Leachate NO_3^- -N decreased curvilinearly with 100% CRF, increased curvilinearly with 50% CRF, 50% LF, and decreased linearly with 100% LF as RP increased. Leachate NH_4^+ -N increased curvilinearly with 100% CRF, showed no significant trend with 50% CRF, 50% LF, and decreased linearly with 100% LF as substrate RP concentration increased. Total leachate N was curvilinearly related with 100% CRF, not related with 50% CRF, 50% LF, and decreased linearly with 100% LF as substrate RP concentration increased. With 100% CRF, total N was lowest (0.14 g) with 25% RP and highest (0.29 g) with no RP.

Substrate physical properties. At planting in 1997, bulk density (D_b) increased and percentage of air space (%AS) decreased with increasing proportions of RP in the substrate (Table 4). At harvest, differences in D_b among substrates were more pronounced, ranging from $0.257 \text{ g} \cdot \text{cm}^{-3}$ with no RP to

Fig. 3. (A) Initial and (B) final pH and (C) initial and (D) final electrical conductivity (EC) of leachate from production of *Spiraea japonica* 'Froebelii' in substrates containing various concentrations of recycled paper (with pine bark) and receiving 100% controlled-release fertilizer (1:0), 50% controlled-release fertilizer and 50% liquid fertilizer (1:1) or 10% liquid fertilizer (0:1) in 1997; $n = 5$. Regression equations for initial pH: 1:0, $y = 4.02 + (2.76 \cdot 10^{-2})x - (2.40 \cdot 10^{-4})x^2$; 1:1, $y = 4.05 + (3.05 \cdot 10^{-2})x - (2.97 \cdot 10^{-4})x^2$; 0:1, $y = 3.79 + (1.93 \cdot 10^{-2})x - (1.37 \cdot 10^{-4})x^2$. Regression equations for final pH: 1:0, $y = 7.12 - (1.12 \cdot 10^{-2})x$; 1:1, nonsignificant; 0:1, nonsignificant. Regression equations for initial EC: 1:0, $y = 1.79 + (4.29 \cdot 10^{-2})x - (2.17 \cdot 10^{-4})x^2$; 1:1, $y = 2.00 + (2.60 \cdot 10^{-2})x$; 0:1, $y = 1.66 + (3.32 \cdot 10^{-2})x$. Regression equations for final EC: 1:0, $y = 0.69 + (5.60 \cdot 10^{-3})x$; 1:1, $y = 0.69 + (3.44 \cdot 10^{-3})x - (3.09 \cdot 10^{-4})x^2$; 0:1, nonsignificant.

0.589 g·cm⁻³ in the 100% RP. Volume reductions ranged from 14.2% in the 25% RP to 52.6% in the 100% RP substrate. While %AS was reduced somewhat (51.3% to 45.9% AS) in the absence of RP from planting to harvest, the reduction was ≈40% (28.8% to 16.9% AS) in the 100% RP substrate. Percentage of porosity showed the same trends as %AS, and cation exchange capacity of substrates increased with increasing proportions of RP.

Discussion

Since production of larger plants is a primary goal of growers, the trade-off between plant growth and the impact of potential nutrient release as environmental pollutants must be considered when evaluating the use of RP as a potential component of growth substrates. Growth (height, diameter, and root and shoot dry weight) declined with increasing proportions of substrate RP during both years (Table 1, Fig. 1). While visual quality was not analyzed objectively, plants in substrates containing ≤50% RP had marketable quality and adequate growth. Chong and Cline (1993) also noted optimum growth in substrates containing ≤30% raw paper mill sludge.

Inhibition of growth at higher concentrations of RP may be attributed to several factors. For optimal growth, substrates should have a total pore space ≥70% and air space of 20% to 30% (Bunt, 1988; Hershey, 1990). Physical properties of substrates containing ≤50% RP were within the acceptable range

(Table 4), but those containing >50% RP had a low initial air space that further decreased over time. Lack of O₂ in the root zone, especially during the first few weeks of growth, may have contributed to low root and shoot dry weights (Table 1, Fig. 1) and inhibited growth in high RP substrates. In addition to their tendency to compact, high RP substrates also had a tendency to form a surface crust that reduced water infiltration and led to excessive surface run-off.

Stunting and chlorosis have been associated with substrates containing significant amounts of wood products (Davidson et al., 2000). These symptoms are related to the C : N ratio of the substrate. Paper is considered a wood-based product. We did not measure C : N ratio of our substrates; however, symptoms and N leaching characteristics in this study seem to be consistent with those of plants exposed to substrates with high C : N ratios in which microorganisms compete with plants for available N.

When porosity was measured, drainage holes were sealed and substrates were allowed to stand in water until saturated (Ingram et al., 1990). However, with normal irrigation, drainage holes were open and much of the water was lost before the substrate was saturated because of surface crusting. Under conditions of luxury water consumption, as may exist in commercial production, crusting of the high RP substrates is less likely. For this reason, estimates of porosity at harvest probably reflect luxury water consumption. However, for this experiment, water-filled

porosity may have been slightly overestimated while air-filled porosity was slightly underestimated.

The EC and pH of all substrates were within the acceptable ranges for adequate nutrient availability (0.1–1.80 dS·m⁻¹ and 5.0–6.5, respectively) during most of the experiment (Warnecke, 1990). Initial pH values were generally <5.0 in 1997 (Table 4), but increased to >5.0 by the second to third irrigation (data not shown). Furthermore, higher pH values at harvest (6.3 to 7.2) were not accompanied by observable symptoms of nutrient deficiency. The use of ammonium nitrate and diammonium phosphate fertilizers, both of which have relatively high salt indices (Tisdale et al., 1993), may have contributed to generally higher EC in LF treatments (Table 3, Fig. 3). In addition, in 1996, because of different substrate water-holding capacities, plants grown in higher proportions of RP were irrigated less frequently, with higher fertilizer concentrations at each irrigation, than were plants grown in substrates with less RP. This fertilizer regime would also contribute to higher EC in substrates containing more RP, indicating that use of CRF may be desirable when RP is used as a substrate under these conditions.

Studies indicate that NO₃⁻ leaching is higher when using LF than CRF (Broschat, 1995; Furuta, 1976; Rathier and Frink, 1989; Yeager et al., 1993). This study supports those findings. As substrate RP concentration increased, NO₃⁻ leaching decreased, particularly in 1996 when irrigation was based on substrate water-holding capacity and maintenance of a uniform leaching fraction regardless of substrate (Table 3). In 1997, when all plants were irrigated with the same volume of water regardless of water-holding capacity, NO₃⁻ leaching decreased as percentage of RP increased for 100% CRF and for 100% LF, but trends were less consistent in the 50% CRF, 50% LF treatment (Fig. 4). Inclusion of RP in the substrate appears to reduce excessive NO₃⁻ leaching.

From this study, we conclude that although N leaching (as NO₃⁻-N, NH₄⁺-N and total N) generally decreased as RP content of the substrate increased, reasonable plant growth occurred in substrates containing ≤50% RP. Therefore, RP can be recommended at rates of up to 50% (by volume) of the growing substrate.

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Fig. 4. Amount of (A) NO_3^- -N, (B) NH_4^+ -N, and (C) total N in leachate from *Spiraea japonica* 'Froebelii' grown in substrates consisting of various proportions of recycled paper to pine bark and receiving 100% controlled release fertilizer (1:0), 50% controlled release fertilizer and 50% liquid fertilizer (1:1), or 100% liquid fertilizer (0:1) in 1997. $n = 5$. Regression equations for NO_3^- -N: 1:0, $y = 0.15 - (3.92 \cdot 10^{-3})x + (3.20 \cdot 10^{-5})x^2$; 1:1, $y = 0.22 - (1.05 \cdot 10^{-3})x + (1.49 \cdot 10^{-5})x^2$; 0:1, $y = 0.36 - (1.00 \cdot 10^{-3})x$. Regression equations for NH_4^+ -N: 1:0, $y = 0.12 - (1.42 \cdot 10^{-3})x + (2.80 \cdot 10^{-5})x^2$; 1:1, nonsignificant; 0:1, $y = 0.60 - (1.27 \cdot 10^{-3})x + (1.14 \cdot 10^{-6})x^2$. Regression equations for total N: 1:0, $y = 0.28 - (5.68 \cdot 10^{-3})x + (6.40 \cdot 10^{-5})x^2$; 1:1, nonsignificant; 0:1, $y = 0.95 - (2.28 \cdot 10^{-3})x$.

Table 4. Physical and chemical characteristics of substrates containing various proportions of recycled paper and pine bark in 1996. $n = 6$.

Recycled paper (%)	Bulk density		Change in vol (%)	Air space (%)		Pore space (%)		CEC (meq/100 g)
	Initial	Final		Initial	Final	Initial	Final	
0	0.208 a ^z	0.257 a	15.4 b	51.3 d	45.9 c	76.5 a	78.8 d	5.5 a
25	0.221 b	0.269 b	14.2 a	40.8 c	46.2 c	72.6 a	76.2 c	12.5 b
50	0.257 c	0.351 c	23.4 c	35.4 b	37.2 b	71.9 a	69.0 b	22.5 c
75	0.275 c	0.448 d	35.8 d	31.9 ab	25.1 a	74.1 a	65.8 ab	30.5 d
100	0.266 c	0.589 e	52.6 e	28.8 a	16.9 a	74.7 a	54.7 a	35.0 e

^zMean separation within columns by SE, $P < 0.05$.

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