Supplementary Irrigation and Mulch Benefit the Establishment of 'Heritage' Primocane-fruiting Raspberry

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ABSTRACT. Field experiments including supplementary trickle irrigation (IR), IRT-76 plastic film (PF), and straw mulch (STR) treatments were conducted during 1993 and 1994 to determine the influence of root-zone temperature and soil moisture status on carbon assimilation and dry mass distribution, and soil and plant nutrient content, during the establishment of *Rubus idaeus* L. 'Heritage' primocane-fruiting raspberries. The IR, PF, and STR treatments were reapplied after the 1993 establishment year to examine their effects on an established, hedgerow planting. Physical environment, vegetative and reproductive data were collected. PF increased root and shoot mass, total flower number, and total berries harvested. Maximum leaf net photosynthetic (Pn) rates were observed under cool air temperatures and root-zone temperature of 25 °C. Field Pn measurements indicated that there was no seasonal decline in Pn. Mulch treatments however, were not beneficial to the established (i.e., 2-year-old) hedgerow planting. The root system of the 2-year-old planting was largely confined to an area within the foliage wall and also at a greater depth from the mulch treatments. Therefore, beneficial effects of mulch management on the growth and development of raspberries may be limited to the establishment year.

Raspberry crop productivity depends on the physical environmental conditions, the genetic components, and an interaction between these two constituents (Privé et al., 1993). Little information is available on how the physical environment influences C assimilation, partitioning or yield components (Dale, 1989). Optimum C assimilation and vegetative growth occur at cool air temperatures (i.e., 17 °C) (Percival et al., 1996; Privé, 1991) and are decreased by drought stress (Goulart, 1989). Cold root-zone soil temperatures in the spring, and excessively hot root-zone soil temperatures in the summer, may hinder raspberry growth in temperate areas such as New York and Ontario (Privé et al., 1993; Trinka, 1991). Controlled environment studies indicate that C assimilation can be influenced by root-zone temperature (Percival et al., 1996), and in conjunction with research by Trinka (1991) and Privé (1991), indicate that a warm root-zone temperature (i.e., 25 °C) is optimum for biomass production. The influence of drought stress on raspberries has yet to be thoroughly examined under field conditions. Past results have indicated that vegetative growth is limited by drought stress under greenhouse conditions (Goulart, 1989) and that plant growth may be more closely correlated to soil moisture than root-zone soil temperature (Trinka and Pritts, 1992). Results from controlled environment experiments by Percival et al. (1996, 1998), indicate that raspberries are sensitive to drought stress with net photosynthesis (Pn) rates dropping upon exposure to stem water potentials less than -1.0 kPa, and raspberry plants exhibiting responses to increasing drought stress.

Additional field experiments are required to further substantiate both greenhouse (Goulart, 1989; Trinka, 1991) and controlled environment (Percival et al., 1998) studies which have examined the influence of root-zone temperature and drought on raspberry growth and development. Particular attention must be focused on the establishment year with sufficient leaf area being required to provide the assimilate supply necessary for the development of the perennial root system (Dale, 1989). The formation of the perennial root system is critical since it is the carbohydrate storage organ for developing primocanes and the major source of primocanes which originate from adventitious buds on the roots (Dale, 1989).

During the establishment year, transplants are often exposed to the extremities of the surrounding environment with no wind protection or partial shade present. The high evapotranspiration rates from the soil surface and plant (Nobel, 1991) contribute to the onset of drought stress and a potential reduction in C assimilation and dry matter production. During the establishment year plants are also exposed frequently to severe weed competition which has a negative effect on raspberry growth and productivity (Trinka and Pritts, 1992). Weed stress effects are a particular concern with tissue-culture propagated or micropropagated (MP) plug transplants, which are more sensitive to cultivation and herbicide programs initiated soon after planting than conventionally propagated bare-root raspberries (Meador, 1985; Mudge et al., 1987; Neal et al., 1990).

The use of IR and mulches are attractive in the establishment phase of raspberries for reducing the risk of drought stress and modifying root-zone temperature while simultaneously minimizing cultivation and herbicide applications (Trinka and Pritts, 1992). PF and STR are inexpensive, readily available, can be mechanically applied, do not leave potentially harmful residues in the soil, do not have a deleterious effect on soil structure, can conserve soil moisture, and modify soil temperature by as much as 5 °C (Trinka and Pritts, 1992). Uncertainty still exists however, on the combined influence of drought stress and root-zone temperature on the establishment and subsequent growth and development in a hedgerow planting. Hence, the specific objectives of this field project were to examine 1) the influence of IR, PF, and STR on root-zone temperature and soil moisture, and 2) the combined effects of IR, PF, and STR on carbon

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assimilation, dry matter distribution, vegetative and reproductive yield components, and plant nutrient content of 'Heritage' raspberries during the establishment and subsequent (i.e., hedgerow) year.

Materials and Methods

PLANT MATERIAL. Dormant *Rubus idaeus* 'Heritage' tissue culture plantlets (Nourse Nurseries, South Deerfield, Mass.) were planted in the greenhouse on 24 and 27 Apr. 1993 and 1994, respectively, for the supplementary irrigation-mulch establishment experiment. Plug plantlets were potted in 10-cm-diameter pots containing Promix-BX (70% peat, 20% perlite, 10% vermiculite + micronutrients) (Les Tourbières Premier LTÉE, Rivière du Loup, Que.), placed on benches in a greenhouse with $22 \pm 3^\circ\text{C}$ day and $17 \pm 1^\circ\text{C}$ night temperatures, and maintained at one unbranched primocane per pot. Plants were exposed to an 18-h photoperiod with supplemental supra-compensation point irradiance (photosynthetic photon flux of $\approx 60 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) provided by overhead 1000-W, high-pressure sodium (HPS) lamps (Lumalux LU1000; GTE Sylvania Canada Ltd, Drummondville, Que.) and were watered and fertilized (20N-8.7P-16.6K at 200 mL/plant) as required. Raspberries were actively growing before transfer to the field for transplanting and had attained ≈ 12 nodes and a height of 20 cm.

EXPERIMENTAL LOCATION. Experiments were conducted during 1993 and 1994 at the Cambridge Research Station which is located at $43^\circ 27' \text{N}$ and $80^\circ 23' \text{W}$, at an elevation of 308 m, on Typic Hapludalf, sandy loam soil. Heat unit accumulation for the 1993 season amounted to 1769 growing degree days (GDD: base 5°C). Heat unit accumulation for the entire 1994 season was unavailable, but was about equal to the 25-year average of 1879 GDD. Experimental sites were preplant fumigated with Basamid Granular (BASF, Rexdale, Ont.) at a rate of 5 kg/100 m^2 before planting. Standard cultural practices for pest control in all trials were followed (Louws, 1990) throughout the 1993 and 1994 growing seasons.

SUPPLEMENTARY IRRIGATION AND MULCH ESTABLISHMENT TRIAL. A split-split-split plot experimental design consisting of four replications was used to examine the influence of supplementary irrigation and mulch on the establishment of 'Heritage' raspberries. The whole, split, split-split, and split-split-split plot factors consisted of planting year (1993 and 1994), supplementary irrigation (IR), infrared transmitting (IRT-76) PF (Second Packaging Inc., Brampton, Ont.), and (STR). Plots were fertilized directly over the rows immediately before planting with granular NH_4NO_3 applied at 130 $\text{kg}\cdot\text{ha}^{-1}$.

Preconditioned plants were transplanted on 31 May 1993 and 30 May 1994 in six-plant plots at a plant density of 60 $\text{cm} \times 3 \text{ m}$ (plant $\times$ row spacing). Both IR and PF (120 cm wide) were installed before planting. The straw mulch (120 cm wide, 8 cm deep) was placed around the plants immediately after planting and trickle irrigation emitters (4 $\text{L}\cdot\text{h}^{-1}$, Canadian Hydrogardens, Ancaster, Ont.) installed. All plants were watered with $\approx 200 \text{ mL/plant}$ of a 10N-52P-10K starter fertilizer solution applied at a concentration of 500 ppm N, and were irrigated as required with overhead sprinkler irrigation for five days to minimize transplant shock.

SUPPLEMENTARY IRRIGATION AND MULCH HEDGEROW TRIAL. The IR, PF, and STR treatments were removed in November, 1993. The same treatments were reapplied in April 1994 with the exception that a 30 cm wide strip was left for primocane emergence to establish a hedgerow planting. Installation of 60 cm mulches on either side of the 30 cm hedgerows, irrigation, and fertigation practices were similar to the establishment trial with the exception that nitrogen was applied as a split application (70% mid-April, 30% in mid-June). Plants were mowed to 2 cm above ground level on 4 May. Canes were not trellised.

PHYSICAL ENVIRONMENT DATA. Root-zone soil temperature was measured throughout the 1994 growing season. Air and root-zone soil temperatures were measured using LI-COR model 1000-16 air temperature and 1000-15 soil temperature probes and recorded hourly on LI-1000 dataloggers (LI-COR Inc., Lincoln, Nebr.). For each treatment, root-zone soil temperature data were collected from three replications at a depth of 15 cm.

Surface reflection coefficients were measured at 1300 HR on 15 July, 18 Aug., and 17 Sept. 1994 in the establishment and 2-year-old hedgerow IR/mulch trials using LI-COR model LI-190S quantum and LI-200S pyranometer sensors attached to a LI-1000 datalogger. Measurements were recorded instantaneously at an equal distance (30 cm) between plants and in the centre of the IR/PF/STR treatments.

Soil moisture adjacent the root zone was monitored with tensiometers (Geneq Inc., Montreal, Que.), which were placed at a depth of 15 cm. Supplementary irrigation was provided daily at 0900 HR when irrometer measurements exceeded 12 kPa, which corresponded to an available water depletion of $\approx 30\%$ (Ley, 1994).

LEAF GAS EXCHANGE. Ambient and leaf chamber CO_2 concentration, air and leaf temperature, vapor pressure deficit and photosynthetic photon flux (PPF) were measured with a LI-6200 portable Pn system equipped with a 0.25 L leaf chamber. Air flow rates were manually adjusted to maintain uniform vapor pressure deficits within the chamber during leaf gas exchange measurement (≈ 270 to 500 $\mu\text{mol}\cdot\text{s}^{-1}$). Calculations of net CO_2 assimilation rate (A), stomatal conductance (gs), leaf temperature and intercellular CO_2 concentration (Ci) were accomplished with a LI-6200 datalogger and supporting software. Ci was calculated from values of A and gs (Caemmerer and Farquhar, 1981).

Leaf gas exchange measurements were recorded between 0500 and 2200 HR, on 14 July, 16 Aug., and 15 Sept. 1994 for the supplementary irrigation-mulch establishment trial and only on 18 July from the 2-year-old hedgerow trial. At each of the sampling intervals, 16 fully expanded and exposed trifoliate leaves per treatment (i.e., one leaf per plant) were randomly selected and monitored. No significant differences existed between treatments in the 2-year-old trial, and consequently, no further leaf gas exchange measurements were recorded.

LEAF CHLOROPHYLL. Twenty-randomly selected, leaf disk samples were collected from each plot. A 1.5-cm leaf disk was punched from each side of the midrib of fully expanded and exposed trifoliate leaves. Chlorophyll was then extracted under nonilluminated conditions in 80% aqueous acetone (Kirk, 1968).

SOIL AND PLANT NUTRITION. Leaf samples were collected on 12 and 15 Aug. 1993 and 1994, respectively. Soil samples were collected by taking six 30-cm-long $\times$ 2.25-cm-wide soil core samples from each plot. Leaf and root samples were analyzed for mineral elements at the Horticultural Research Institute of Ontario (Vineland Station, Ont.) and soil samples were analyzed for mineral nutrients at the Nutrient Analytical Services Lab, Department of Land Resource Science, Univ. of Guelph (Guelph, Ont.). Nitrogen was analyzed as described by Isaac and Johnson (1976), and K, Ca, and Mg were determined using the method of Dahlquist and Knoll (1978).

VEGETATIVE AND REPRODUCTIVE YIELD COMPONENTS. Vegetative and reproductive data were collected on six randomly selected canes per plot at the conclusion of the growing season as outlined by Daubeney et al. (1986). All plants were dug at the conclusion of the 1994 growing season with a front-end loader tractor. Root systems were washed with a power-washer to remove soil. This allowed the recovery of most of the root system. Measurements were collected on root mass, macronutrients, and the number of adventitious shoots originating from root nodes.

Fig. 1. Influence of supplementary irrigation (IR), plastic film (PF), and straw mulch (STR) on root-zone temperature (depth of 15 cm) of select treatments in the 1994 establishment trial. Each point represents an average of three measurements.

DATA ANALYSIS. Analysis of variance was completed using the General Linear Model procedure of SAS (SAS Institute, Cary, N.C.).

Results and Discussion

ROOT-ZONE PHYSICAL ENVIRONMENT. In the establishment trial, there was a profound influence of IR on root-zone soil temperature during the summer due to the increased soil heat capacity of the IR treatments. This result agrees with those of Oke (1987), resulting in lower root-zone soil temperatures (Fig. 1). STR reduced root-zone soil temperatures during the day in July and August by providing an insulating layer, which resulted in high shortwave and longwave reflection coefficients and reduced energy flux into the soil (Table 1) while simultaneously conserving moisture supply (Table 1). PF reduced the shortwave reflection coefficient, increased the emissivity of the soil surface (Table 1), and inhibited the release of latent heat (Fig. 1). This resulted in increased soil temperatures, which were as much as 25 °C higher at the soil surface than under the STR treatments (data not shown). At a depth of 15 cm however, this temperature differential was minimized to 5 °C in July (Fig. 1), and was nearly undetectable at the onset and conclusion of the growing season (data not shown) due to decreased radiation intensity and duration, and reduced air temperatures (e.g., Fig. 1).

SUPPLEMENTARY IRRIGATION AND MULCH ESTABLISHMENT TRIAL. Modification of the root-zone environment with IR, PF, and STR treatments had a direct impact on dry matter production. Shoot and root dry mass of the +PF treatments were 25% and 23% greater respectively, than the -PF treatments (Table 2). No significant IR or STR effects were observed (Table 2). The water conserving characteristics of PF and STR were demonstrated by the high soil moisture contents of the three -IR treatments with PF and STR (Table 1). This was particularly apparent with the -IR/-PF/-STR (control) treatment having 56% less total dry mass than the other three -IR treatments and 62% less total dry mass than the combined +IR treatments (Table 2).

These results add support to the findings of Trinka and Pritts (1992) and Privé et al. (1993) that root-zone temperature influences dry matter production in raspberry. With the exception of the control treatment, plant performance in 1993 and 1994 was directly related to root-zone soil temperature with the +PF treatments having a

Table 1. Supplementary trickle irrigation (IR), plastic film (PF), and straw mulch (STR) influence the shortwave, longwave, and total radiation reflection coefficients and root-zone soil moisture of 'Heritage' raspberries during the 1994 establishment growing seasons.

			Reflection coefficients			Root-zone		
			Shortwave	Longwave	Total	soil moisture (–kPa)		
Treatment			(400–700 nm)	(700–1100 nm)	(400–1100 nm)	14 July	16 Aug.	15 Sept.
–IR	–PF	–STR	0.087	0.26	0.19	41	28	34
		+STR	0.073	0.28	0.20	23	17	21
	+PF	–STR	0.076	0.26	0.19	26	25	29
		+STR	0.081	0.31	0.22	19	24	20
+IR ²	–PF	–STR	0.085	0.25	0.19	8.0	7.8	7.1
		+STR	0.080	0.37	0.25	5.9	6.9	6.4
	+PF	–STR	0.072	0.30	0.21	9.1	7.2	6.1
		+STR	0.077	0.31	0.22	6.2	5.8	5.9
Significance			PF***	IR*	IR***	IR***	IR***	IR***
			STR**	STR**	STR***	STR**	STR*	STR*
			IR × PF**	PF × STR***	PF × STR*	IR × PF*	IR × PF*	
			PF × STR**	IR × PF × STR***	IR × PF × STR***			
			IR × PF × STR***					

²Supplementary irrigation was applied with individual 4.0-L-h⁻¹ emitters located at each plant with water quantity governed by irrometers located at a depth of 15 cm.

***, ** Significant *P* = 0.05, 0.01, or 0.001 by analysis of variance. Data were analyzed as a split-split-plot experimental design with the whole-plot factor consisting of supplementary irrigation (IR), split-plot factor consisting of plastic film (PF), and the split-split-plot factor consisting of straw mulch (STR).

Table 2. Effects of supplementary trickle irrigation (IR) and mulch [plastic film (PF) and straw (STR)] on dry matter accumulation and vegetative and reproductive components of 'Heritage' raspberries at the conclusion of the 1993 and 1994 establishment growing seasons.

						Vegetative yield				Reproductive yield		
			Dry mass (g) ^x			Root to shoot ratio	Vegetative			Floral and fruit (no.)	Fruit harvested (no.)	Fresh fruit mass (g)
Treatment			Root	Shoot	Total		Vegetative laterals (no.)	lateral length (cm)	Adventitious shoots (no.)			
-IR	-PF	-STR	33.4	93.6	180	0.757	3.95	36.2	1.43	44.4	13.6	1.72
		+STR	41.0	78.6	214	0.961	3.91	40.2	1.29	41.7	12.2	1.83
	+PF	-STR	51.9	108	295	0.937	4.40	45.1	1.21	40.5	20.3	1.91
		+STR	48.1	109	288	0.926	4.10	46.8	0.969	43.7	26.6	1.89
+IR ^z	-PF	-STR	46.6	99.3	278	1.01	4.41	42.9	1.91	32.2	14.4	1.87
		+STR	43.9	85.4	247	1.17	4.01	40.8	2.23	27.5	13.3	1.94
	+PF	-STR	54.2	118	316	0.914	5.49	42.7	3.57	34.5	22.6	2.04
		+STR	49.2	111	323	0.911	4.89	45.3	0.800	32.9	17.2	2.01
Significance		PF***	PF***	PF***	NS	IR** PF**	NS	STR* PF × STR*	PF***	PF × STR*	IR*	

^zSupplementary irrigation was applied with individual 4.0-L-h⁻¹ emitters located at each plant with water quantity governed by irrometers located at a depth of 15 cm.

NS, *, **, *** Significant $P = 0.05, 0.01, \text{ or } 0.001$ by analysis of variance. Data were analyzed as a split-split-plot experimental design with the whole-plot factor consisting of supplementary irrigation (IR), split-plot factor consisting of plastic film (PF), and the split-split-plot factor consisting of straw mulch (STR).

^xAll dry mass and yield components are reported on a per cane basis. Root dry mass and root to shoot ratio results are reported only from 1994.

significantly higher dry mass than +STR treatments (Table 2). These results also add support to the hypothesis that despite the presence of both stomatal and root-controlled drought response mechanisms, Pn can be reduced by drought stress (Percival et al., 1998).

PF increased the vegetative and reproductive yield components with the +PF treatments having more vegetative laterals, flowers, and a higher proportion of harvested fruit (Table 2). The increase in vegetative lateral number resulted from shoots originating from basal buds situated near the crown. It can be speculated that the vegetative lateral number increase and the maturity advancement observed in the PF treatments may have been a result of an alteration in the balance of endogenous plant growth regulators. Root tips are a major source of cytokinins (Horgan, 1986) and by elevating root-zone temperature, endogenous cytokinin synthesis may have increased. This may have resulted in cytokinin-promoted lateral bud develop-

ment (i.e., formation of vegetative laterals) (Salisbury and Ross, 1992) and enhanced cell expansion resulting in marginally larger leaves (data not reported), and advanced maturation (Horgan, 1986).

IR and mulch had a drastic effect on soil nutrient content (Table 3). IR had the largest influence with significant reductions in soil N, P, K, and Mg levels observed by August (Table 3). Although part of this reduction could be attributed to increased plant uptake in the +IR treatments, most of the difference between +IR and -IR treatments was presumably due to nutrient leaching through the very coarse, sandy loam (depth of ≈ 35 cm), which was situated over a sand (C_q) mineral horizon (Hausenbuiller, 1985; Nye and Tinker, 1977; Peryea, 1994). The +PF treatments may have also reduced N, K, and Mg loss to leaching and N volatilization (Hausenbuiller, 1985) with NO₃ levels of +PF treatments being significantly higher than -PF treatments (Table 3).

Table 3. Influence of supplementary trickle irrigation (IR), plastic film (PF), and straw mulch (STR) on soil, root, and leaf nutrient content of 'Heritage' raspberries in August 1993 and 1994 of the establishment year.

			Soil nutrient content (mg·kg ⁻¹ dry mass)					Plant nutrient content (mg·kg ⁻¹ dry mass) ^y						
Treatment			NO ₃	NH ₄	P	K	Mg	N		K		Ca		
								Root	Leaf	Root	Leaf	Root	Leaf	
-IR	-PF	-STR	2.08	4.81	67.0	156	98.5	1.68	3.00	1.08	2.16	1.29	1.12	
		+STR	2.21	4.74	67.5	175	93.5	1.75	2.87	1.25	2.24	1.07	1.22	
	+PF	-STR	29.0	5.16	69.3	184	121	1.73	2.98	1.16	2.28	1.29	1.19	
		+STR	19.5	6.17	68.8	193	113	1.68	2.97	1.16	2.15	1.16	1.23	
	+IR ^z	-PF	-STR	5.17	7.21	54.5	119	92.8	1.67	2.94	1.14	2.09	1.21	1.08
		+STR	5.24	7.83	63.5	148	93.8	1.62	3.01	1.29	2.22	1.17	1.18	
	+PF	-STR	10.4	9.37	59.3	139	90.8	1.62	3.01	1.21	2.19	1.12	1.18	
		+STR	9.53	8.34	60.5	152	99.5	1.74	2.88	1.16	2.24	1.16	1.14	
Significance ^z			IR***	IR***	IR***	IR***	IR***	NS	NS	PF × STR***		NS	STR***	STR**
			PF***	PF**		PF**	PF***						IR × STR**	
			IR × PF*		STR***		IR × STR**							

^yPlant nutrient content is presented on a mg·kg⁻¹ dry mass basis. Shoot nutrient results were collected in 1993 and 1994, whereas root nutrient results were collected only in 1994.

***, **, * Significant $P = 0.05, 0.01, \text{ or } 0.001$ by analysis of variance. Data were analyzed as a split-split-plot experimental design with the whole-plot factor consisting of supplementary irrigation (IR), split-plot factor consisting of plastic film (PF), and the split-split-plot factor consisting of straw mulch (STR).

Fig. 2. Influence of supplementary irrigation (IR), plastic film (PF), and straw mulch (STR) on net photosynthesis of select treatments of 'Heritage' raspberry during the 1994 establishment season. Each value represents the mean of eight measurements, with mean separation for each time interval completed using Duncan's new multiple range test at $P = 0.05$.

The underlying factors governing nutrient uptake by a plant are total surface area of a root system, inherent rates of absorption, contact with surrounding soil and physical environment variables (Peryea, 1994). However, despite large differences in soil nutrient content (Table 3) and root-zone environmental conditions (Table 1, Fig. 1), no significant differences in root N, leaf N, and leaf K, and only marginal differences (i.e., <8%) in root K, root Ca, and leaf Ca, were present in this study (Table 3). Root and shoot nutrient status remained within relatively narrow limits indicating that a functional equilibrium existed between the root and shoot system (Table 3). Such results have been shown for a number of plant species exposed to many different experimental and environmental conditions (Richards, 1980; Thornley, 1975) and indicate that alterations in the activities of the shoot and root system, and also possible alterations in the shoot to root ratio, may lead to the maintenance of a constant internal nutrient status.

The large differences in leaf gas exchange values obtained in this study throughout the 1994 growing season were more related to physical environment conditions of the root and shoot than intrinsic photosynthetic capacity differences (e.g., chlorophyll quantity). There was a significant influence of IR on chlorophyll with the -IR and +IR treatments having 29.1 and 27.3 $\mu\text{g}\cdot\text{cm}^{-2}$ chlorophyll a, and 41.6 and 39.0 $\mu\text{g}\cdot\text{cm}^{-2}$ total chlorophyll respectively. The field Pn results obtained throughout 1994 verified the Pn results reported from controlled environment studies (Percival et al., 1996), with maximum Pn rates observed under conditions of saturated radiation (Fig. 2), cooler air and warm root-zone temperatures (Fig. 1), sufficient soil

moisture (Table 1), and low vapor pressure deficits (i.e., high relative humidity). In particular, the manipulation of the root-zone physical environment through the use of +IR, +PF and +STR had a significant impact on Pn in July of 1994. The two -IR treatments had maximum rates at 1100 HR and exhibited a decline of 57% by 1500 HR, while only a 9.8% decline in Pn was present with the two +IR treatments (Fig. 2). Associated with the midday Pn decline was a parallel (63%) decrease in transpiration with -IR treatments, and a slight (<3 °C) increase in leaf temperature.

Past research has attributed the observed midday Pn decline to an accumulation of starch in red raspberry (Cameron et al., 1993) resulting in a feedback inhibition in the photosynthetic cycle. This is possibly due to increased CO₂ diffusion resistance toward the carboxylation enzymes (Grub and Mächler, 1990; Ho, 1992), a light transmission interference within the chloroplast (Ho, 1992) or biochemical effects of sugar or starch accumulation (Blechsmidt-Schneider et al., 1989; Grub and Mächler, 1990). Although no leaf carbohydrate data were collected, it appears improbable that the midday decline noted in this study was due only to leaf starch content. This is apparent with the two +IR treatments (e.g., cooler soils) exhibiting no midday decline, and only a small decrease in Pn rate of <15%, which can be attributed to temperature effects on carboxylation efficiency (Fig. 2) and increased dark respiration (Percival et al., 1996).

The midday decline in Pn observed in the -IR treatments could have also occurred if root-zone temperatures became supraoptimum (i.e., air and root-zone temperatures >17/25 °C) resulting in a root-controlled decline in assimilation due to mechanisms such as low nutrient supply or an alteration in ionic and plant growth regulator relations (Schulze, 1990). The midday decline could also be caused by drought stress (Table 1) resulting in a feedback inhibition of Pn (Percival et al., 1998). More research, however, is required to determine the mechanisms involved with root-zone temperature effects on Pn.

Throughout the 1994 growing season Pn exhibited maximum rates of $\approx 15 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (Fig. 2). However, unlike the results of Fernandez and Pritts (1994), no seasonal decline in Pn was observed,

Table 4. Effects of supplementary trickle irrigation (IR), plastic film (PF), and straw mulch (STR) on dry matter accumulation of a 2-year-old hedgerow planting of 'Heritage' raspberries at the end of the 1994 growing season.

			Dry mass accumulation (g)		
Treatment			Root (g·m ⁻¹)	Shoot (g/cane)	Root:shoot ratio
-IR	-PF	-STR	406	47.5	0.430
		+STR	440	44.3	0.419
	+PF	-STR	417	42.0	0.420
		+STR	467	39.5	0.424
+IR ^z	-PF	-STR	593	48.9	0.525
		+STR	667	50.1	0.497
	+PF	-STR	687	50.3	0.562
		+STR	639	40.2	0.583
Significance ^y			IR ^{***}	NS	IR [*]

²Supplementary irrigation was applied with individual 4.0-L·h⁻¹ emitters located at each plant with water quantity governed by irrometers located at a depth of 15 cm.

***, ** Significant $P = 0.05$, 0.01, or 0.001 by analysis of variance. Data were analyzed as a split-split-plot experimental design with the whole-plot factor consisting of supplementary irrigation (IR), split-plot factor consisting of plastic film (PF), and the split-split-plot factor consisting of straw mulch (STR).

possibly due to the establishment plants not having the same source-sink relationship or endogenous plant growth regulator balance as summer bearing raspberries. With the presence of a rapidly growing root system, endogenous cytokinin levels may have been sustained longer in the growing season resulting in hormonal control over seasonal Pn decline (Richards, 1980).

SUPPLEMENTARY IRRIGATION AND MULCH 2-YEAR-OLD HEDGEROW TRIAL. The PF and STR treatments did not affect root-zone soil temperature or moisture due to shading of the mulch by the foliage. In the second year, the hedgerow root system also had vertically expanded with the majority of the root system situated further from the mulches and soil surface (i.e., 15 to 20 cm vs. 12 to 15 cm for the establishment year). As a result, only a +IR effect on root mass was observed at the conclusion of the season with IR treatments having a 33% greater root dry mass than -IR treatments (Table 4). All treatment effects on vegetative and reproductive components were minimal with no effect on shoot density (24.1 ± 2.83 canes/m), dormant adventitious shoot number (48.9 ± 4.46 buds/m), node number (29.4 ± 3.81 nodes/cane), cane diameter (8.94 ± 2.36 mm), total floral and berry number (30.3 ± 2.83 /cane), berry number harvested (8.18 ± 2.27 /cane), or berry fresh mass (g/berry). There was also no influence of mulch on leaf nutrient content, chlorophyll content, or leaf gas exchange (data not shown).

Therefore, in a dense, primocane-fruiting, hedgerow planting, the use of mulches is not warranted due to exclusion of the mulches and root-zone from direct radiation and because the majority of the root system is situated at a greater distance from the mulch and soil surface than in an establishment planting. The use of IR however, will result in increased root mass, and to a lesser extent, fruit mass. The increase in root mass associated with IR is of particular importance in a hedgerow planting because the carbohydrate supply required for new primocane growth originates from the root system (Dale 1989).

In conclusion, this field study provides additional knowledge of the fundamental biology of the raspberry, and valuable insights into management strategies to attain improved vegetative growth and subsequent yield efficiency. PF should be used in raspberry production only in the establishment year. PF will increase root-zone soil temperature and reduce weed competition resulting in increased shoot and root system development. Use of PF in an established hedgerow planting was not beneficial due to the root system being largely shaded by the canopy, and also at a greater depth from the mulch treatments. STR should only be used where symptoms of drought stress persist. Supplementary irrigation is an important management tool that can be used throughout the establishment and subsequent hedgerow phases of raspberry production.

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