J. Amer. Soc. Hort. Sci. 127(5):776–780. 2002.

Genotype/Genotype × Environment Biplot Analysis for Cultivar Evaluation and Mega-environment Investigation in Primocane-fruiting Red Raspberry

J.A. Sullivan,[1] Weikai Yan,[2] and J.P. Privé[3]
Department of Plant Agriculture, University of Guelph, Guelph, Ontario, N1G 2W1 Canada

Additional index words. fall-bearing, genotype × environment, yield

Abstract. **Primocane-fruiting (PF) red raspberry (*Rubus idaeus* L.) cultivars are being grown in many regions as their popularity increases. However, testing of this perennial fruit crop is expensive and requires many years. Large genotype (G) × environment (E) interactions can make identification of superior genotypes difficult. The G/G × E (GGE) biplot can be used to measure cultivar performance and group locations into mega-environments. The GGE biplot was applied to yield trial data of three PF red raspberry cultivars Autumn Bliss, Heritage, and Redwing grown in 17 environments (year–location combinations). The 17 environments encompassed six locations in Ontario and Quebec, Canada between 1989 and 1996. 'Autumn Bliss' produced the highest yields in 11 of 17 environments. 'Heritage' was usually the lowest yielding cultivar. Two mega-environments were identified based on the performance of 'Autumn Bliss' and 'Redwing'. Some environmental variables were likely to be responsible for the discriminating ability of the test environments as they were correlated with the primary effects. The GGE biplot was an effective analysis to determine mega-environments and the cultivars best adapted to each.**

Primocane-fruiting (PF) or fall-bearing red raspberry (*Rubus idaeus*) production continues to expand rapidly in North America as new productive cultivars are released from breeding programs (Fiola, 1999). PF raspberries are often grown as annuals where the first year canes are removed after fruiting and a new set of canes emerges each spring from the perennial root system. Yield trials and research have revealed large genotype × environment interactions (GE) associated with PF cultivars (Hoover et al., 1988, Privé et al., 1993a, 1993b). The presence of large GE interactions represent special challenges for plant breeders working with perennial fruit crops such as raspberry.

Raspberry cultivars often benefit from testing over wide areas to identify adaptability to different climatic regions and winterhardiness levels. Winterhardiness in PF cultivars is a lower priority compared to summer-bearing cultivars, however, Privé et al. (1993a) indicated that at northern latitudes winterhardiness of roots was a concern.

Yield trials are often the most expensive and resource-consuming aspect of a plant breeding program. This is especially true for perennial fruit crops which are often tested for several years at a location. Years and locations are both important sources of variation when data from multiple environment trials are examined. One way of increasing efficiency of yield trials is to know if the target region for the cultivar belongs to a single mega-environment or is comprised of different mega-environments (Yan and Hunt, 1998). This will have implications for the number of locations and years and geographic distribution of test sites required for testing. A mega-environment is defined as a growing region with a homogenous environment that causes similar genotypic responses (Gauch and Zobel, 1997). For instance, Yan et al. (2000) identified two mega-environments in Ontario for winter wheat (*Triticum aestivum* L.) cultivar testing where up to five regions existed previously.

The performance of a cultivar is comprised of three effects; genotypic main effect (G), environment main effect (E), and GE interaction but only the G and GE components are relevant. Yan et al. (2000) proposed the GGE biplot to emphasize that G and GE interaction must be considered simultaneously in cultivar evaluation. The GGE biplot is a visual display of the G + GE of multi-environment trial data. It presents groups of locations that produce similar cultivar responses and identifies the highest yielding cultivars for each group. The GGE biplot is constructed using the first two principal components (PC 1 and PC 2) derived from environment-centered data of multi-environment trials. Since the genotype PC 1 scores tend to correlate highly with the genotype means, the ideal cultivar would possess large scores for PC 1 indicating high average yield and small absolute scores for PC 2 indicating less GE interaction and greater stability. The biplot can also be used to compare testing environments for their ability to differentiate between cultivars. The ideal test environment would have a large PC 1 score (greater discrimination) and small PC 2 score (less GE interaction and are representative of the overall environment). The GGE biplot effectively addresses the question of which cultivar had the best performance at each location and exploits both G and GE.

Yan et al. (2001) proposed a further refinement of their original model to replace PC 1 using Mandel's (1961) sites regression on genotypic main effect. This change made the original model more interpretable. Later it was found that GGE biplot based on the original model is equally interpretable if an average environment coordinate is used (Yan, 2001).

The objective of this study was to use the GGE biplot to examine GE interaction and identify mega-environments for Ontario, Canada, in a perennial fruit crop, PF red raspberry. This is an extension of research conducted originally by Privé et al. (1993a, 1993b) and Sullivan and Privé (2001) where performance of cultivars and effects of several environmental variables on yield stability of PF raspberries were measured.

Materials and Methods

Three PF raspberry cultivars—Autumn Bliss, Heritage and

Received for publication 24 June 2001. Accepted for publication 29 Apr. 2002.
[1]Horticultural Science Division. Corresponding author; e-mail asulliva@uoguelph.ca.
[2]Crop Science Division.
[3]Present address: Agriculture and Agri-Food Canada, Senator Herve J. Michaud Research Station, P.O. Box 2069, Bouctouche, New Brunswick E4S 2J2, Canada.

Redwing—were grown at six locations in Ontario and Quebec, Canada, including sites near Harrow, Vineland, Cambridge, Kemptville, New Liskeard, and Lavaltrie (Quebec). These sites provided different environments with a range of latitudes (i.e., daylength), mean temperature, length of growing season, soil type, and moisture conditions. The plantings were established in 1985 using a completely randomized design with five replications of each cultivar. Each replication consisted of five plants which were allowed to produce a hedgerow ≈3.0 m in length. Details of locations and cultural practices were described previously in Privé et al. (1993a) and Sullivan and Privé (2001).

Fruit were harvested and weighed at all locations in 1989 and 1990 except at Kemptville in 1989. Harvest continued at the Cambridge location between 1991 and 1996. Yield was determined from a random sample of five canes per plot and used with cane number to estimate yield per square meter (Dale and Daubeny, 1985). Analysis of variance (ANOVA) was performed on two data sets, all locations in 1989 and 1990 (11 locations and years), and Cambridge location from 1991 to 1996 (6 years).

The GGE biplot analysis has been described in detail in Yan et al. (2001) and the graphical analysis presented in Yan (2001). Briefly the analysis is based on

$$Y_{ij} = \beta_j + b_j\alpha_i + \lambda_1\xi_{i1}\,\eta_{j1} + \varepsilon_{ij} \quad [1]$$

where Y_{ij} is the average yield of genotype i in environment j, β_j is the average yield of environment j, α_i is the main effect of genotype i, and b_j is the regression coefficient of the environment centered yields in the jth environment on the genotype main effects, λ_1 is the singular value for first principal component, ξ_{i1} and η_{j1} are the eigenvectors for genotype i and environment i for the first principal component, and ε_{ij} is the residual for genotype i in environment j.

To display the primary ($b_j\,\alpha_i$) and secondary effects ($\lambda_1\xi_{i1}\,\eta_{j1}$) in a biplot, Eq. [1] is written in the form of

$$Y_{ij} - \beta_j = b^*_j\alpha^*_i + \xi^*_{i1}\eta^*_{j1} + \varepsilon_{ij} \quad [2]$$

where $\xi^*_{i1} = \lambda_1^A\,\xi_{i1}$, $\eta^*_{j1} = \lambda^{1-A}\,\eta_{j1}$, $b^*_j = Bb_j$, and $\alpha^*_i = B^{-1}\,\alpha_i$, with

$$A = 0.5\left\{1 + \frac{\ln\left(\dfrac{\max(\eta_{j1}) - \min(\eta_{j1})}{\max(\xi_{i1}) - \min(\xi_{i1})}\right)}{\ln\lambda_1}\right\} \quad [3]$$

and $B = \sqrt{[\max(\alpha_i) - \min(\alpha_i)]/[\max(b_j) - \min(b_j)]}$ [4]

A and B are so defined that the biplot space used by the genotypes and the locations (environments) are the same. The biplots were constructed and examined following Yan et al. (2000, 2001). Graphical presentation of the data was prepared using the GGE biplot software (Yan, 2001).

The environmental scores b_j^* and η^*_{j1} were correlated with the environmental measurements for the 11 year–location combinations published originally by Privé et al. (1993b). Detailed environmental measurements were not available for the 1991 to 1996 seasons at Cambridge. The Corr procedure of SAS (SAS Inst., Inc., 1999) was used to calculate the Pearson correlation coefficients between environmental scores and the environmental measurements. Briefly, the environmental measurements included cumulative solar radiation, daylength, air and soil temperatures, and water (a combination of precipitation and irrigation) for each month from April to October.

Results

The ANOVA for fruit yield in six locations in 1989 and 1990 and for 6 years at Cambridge only are presented in Table 1. Significant year × location × cultivar effects were observed for the 1989–90 experiment. The year × cultivar effects were nonsignificant only for the Cambridge experiment. The primary and secondary effects (Table 2, Fig. 1) represent the G and GE interactions, respectively. The G scores for the primary effect represent average yield or general adaptation of the genotypes. The genotype scores of the secondary effect represent the GE interactions attributable to each genotype and indicate stability or specific adaptation. 'Autumn Bliss' had the greatest average yield followed by 'Redwing' and 'Heritage'. Based on its position relative to the primary effects (i.e., x-axis) the general adaptation of 'Heritage' was much lower than either of the other two cultivars. However, 'Heritage' demonstrated greater stability followed by 'Autumn Bliss' and 'Redwing' (i.e., lower absolute secondary effects). However, this only indicates that 'Heritage' was consistently poor yielding. Similar results were obtained with the Cambridge data for 1991 to 1996. At the Cambridge location, several patterns were observed. Firstly, this was clearly a location that favors 'Autumn Bliss'. 'Autumn Bliss' had the highest yield in all years except in 1991 and 1995. Secondly, years could be classified into two groups, i.e., the early years (1989 and 1990) when average performance was high and 'Autumn Bliss' was obviously superior over others (Table 1), and the middle and later years when fruit yield of all cultivars stabilized at a lower level. Thirdly, 1995 was an anomaly with 'Heritage' outperforming the other two cultivars (Fig. 2).

SUPERIOR GENOTYPES AND MEGA ENVIRONMENT IDENTIFICATION.

Table 1. ANOVA for fruit yield of three PF red raspberry cultivars grown at six locations in 1989 and 1990 and at one location from 1991 to 1996.

	Six locations in 1989 and 1990		One location from 1991 to 1996	
Source	df	Mean square	df	Mean square
Locations (L)	5	238,857**		
Cultivars (C)	2	57,826**	2	18^{NS}
L × C	10	5,511**		
Error	71	912		
Year (Y)	1	19,698*	5	198**
Y × L	5	18,990*		
Y × C	2	2,055^{NS}	10	9^{NS}
Y × C × L	10	2,300*		
Error	59	1,292	62	6

^{NS,*,**}Nonsignificant or significant at $P < 0.1$ or 0.05, respectively.

To identify the mega-environments the three genotypes were connected by dotted lines (Fig. 1) and a perpendicular line to each side of the triangle passing through the origin was added. The environments were divided between two major sectors. The first sector contains the two environments, Harrow 1989 and Vineland 1990, with 'Redwing' the superior cultivar and the second sector contains all other environments with 'Autumn Bliss' the superior cultivar. 'Heritage' was superior in none of the environments and its exclusion from the other two sectors indicated it yielded poorly in all environments. These data suggest two mega-environments for PF raspberries namely the 'Redwing' winning niche and the 'Autumn Bliss' winning niche. The environments above and below the perpendicular between 'Redwing' and 'Autumn Bliss' represent better performance of 'Redwing' and 'Autumn Bliss', respectively. However, examining the distribution of locations within the two mega-environments reveals that the Harrow and Vineland sites occur in both mega-environments. For the Cambridge site only (Figs. 1 and 2), 1 of 8 and 6 of 8 years were in the 'Redwing' and 'Autumn Bliss' niches, respectively.

Better locations for cultivar evaluation. As Yan et al. (2000, 2001) reported, those locations best able to identify high-yielding, stable genotypes are characterized by large primary effects and close to zero secondary effects. The better environments for testing based on this rating were Lavaltrie in 1989 and Cambridge in 1992 and 1993 (Figs. 1 and 2). Environments such as Cambridge in 1989 and 1990, and Harrow and Lavaltrie in 1990, had large primary effects but were also accompanied by higher (i.e. >2.04) secondary effects (Table 2).

In 1990, the Vineland environments had average yields that were 3.9 times greater than the next highest environment (Lavaltrie 1990) (Table 2). However these two environments also had two of the four greatest GE or secondary effects. At Vineland, there was a very strong cultivar × year crossover effect for fruit yield for 'Autumn Bliss' and 'Redwing' while fruit yield of 'Heritage' differed by only 1.0 kg·m^{-2} or 3.1% between years. 'Heritage' failed to produce any crop at New Liskeard due to early fall frosts in both seasons. The primary and secondary scores for the New Liskeard environments places them very close to the biplot origin meaning that all cultivars performed similarly. New Liskeard in 1989 and 1990 were the shortest seasons and had extremely low yields. This location along with Lavaltrie (1989) and Kemptville (1990) contributed very little to GE effects. These locations had the least ability to discriminate between cultivars.

Correlation between primary and secondary effects and environmental variables. A significant correlation between primary or secondary effects and environmental variables indicates that some of the factors contributed to discrimination of the cultivars. Daylength was correlated with primary effects for August (r = –0.59) (P = 0.05) and October (r = –0.63) (P = 0.04). Solar radiation was correlated with primary effects only in September (r = 0.59) (P = 0.05). Air temperature and primary effects were only correlated for October (r = 0.67) (P = 0.03). Environmental variables and secondary effects were not correlated.

Discussion

In the biplot analysis, greater genotype stability was represented by smaller absolute values for secondary effects. 'Heritage' had the greatest stability for yield followed by 'Autumn Bliss', and 'Redwing' was the least stable cultivar. Sullivan and Privé (2001) also found a similar ranking of these cultivars for yield stability using different regression models and 14 of the 17 locations and years that were used in the current study. In the three

Table 2. Fruit yield, genotype and genotype × environment effects for three PF red raspberry cultivars grown in two trials.

					Year–location effects[z]	
		Yield (kg·m^{-2})			Primary	Secondary
Location	Year	'Autumn Bliss'	'Heritage'	'Redwing'	(b_i^*)	(η_{i1}^*)
Cambridge	1989	9.8	1.7	4.2	4.52	2.26
Cambridge	1990	12.4	4.5	10.8	4.53	–2.04
Harrow	1989	5.5	3.7	10.6	1.28	–6.59
Harrow	1990	12.8	4.5	11.5	4.81	–2.59
Kemptville	1990	5.2	2.6	3.1	1.45	–1.02
Lavaltrie	1989	5.1	1.8	4.0	1.88	–0.47
Lavaltrie	1990	14.8	5.9	8.4	4.94	2.78
New Liskeard	1989	0.4	0.0	0.5	0.23	–0.36
New Liskeard	1990	0.1	0.0	0.1	0.08	–0.03
Vineland	1989	44.5	32.2	36.3	6.81	3.01
Vineland	1990	35.9	33.2	42.1	1.79	–8.24
Genotype effects[z]						
Primary (α_i^*)		10.29	–11.08	0.79		
Secondary (ξ_{i1}^*)		4.02	3.21	–7.22		
Cambridge	1991	16.3	14.0	17.3	1.90	0.86
Cambridge	1992	7.6	4.0	7.4	2.37	–0.31
Cambridge	1993	6.2	4.5	5.9	1.04	–0.38
Cambridge	1994	10.3	9.4	7.6	–0.36	–2.54
Cambridge	1995	7.2	9.6	8.3	–1.19	1.10
Cambridge	1996	6.1	5.0	4.2	0.06	–1.80
Genotype effects[z]						
Primary (α_i^*)		1.58	–3.37	1.79		
Secondary (ξ_{i1}^*)		–1.86	0.08	1.78		

[z]Genotype and year–location effects are defined and calculated in Yan et al. (2000, 2001).

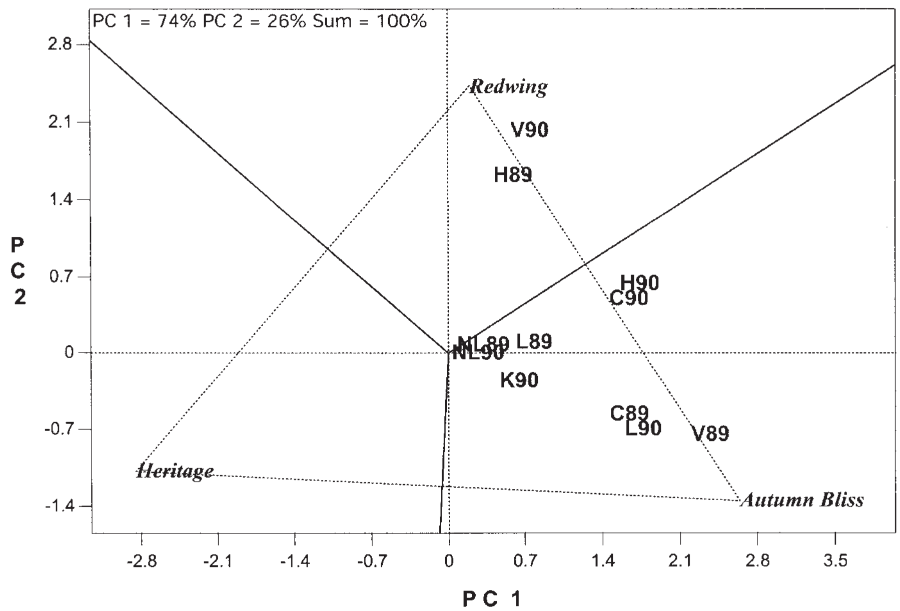


Fig. 1. The GGE biplot for fruit yield based on 1989 to 1990 trial data. The full environment names followed by years are C = Cambridge, H = Harrow, K = Kemptville, L = Lavaltrie, NL = New Liskeard, and V = Vineland. PC 1 and PC 2 = primary and secondary effects, respectively.

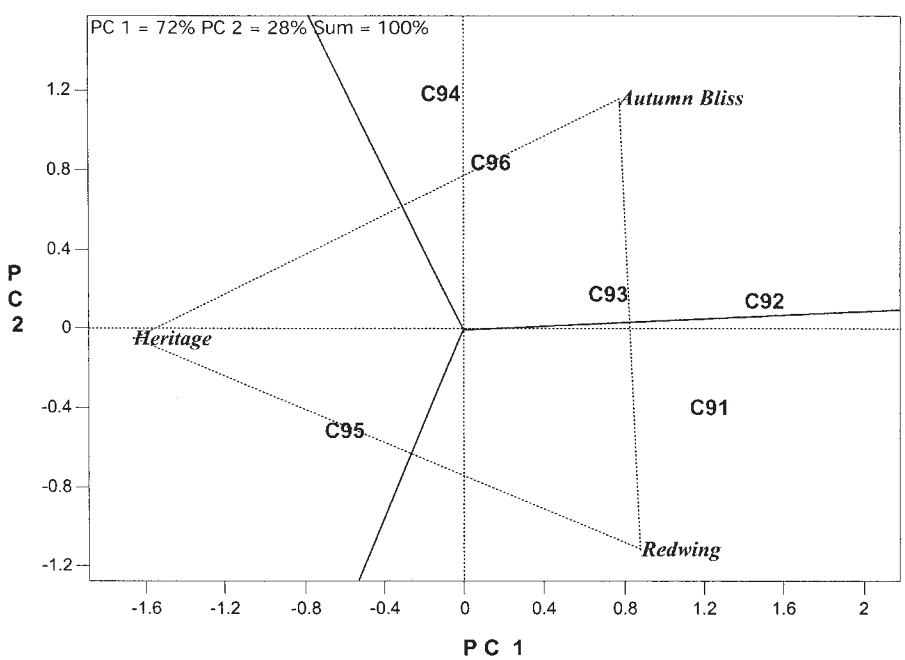
environments new to this study (i.e., Cambridge, 1994, 1995, 1996) significant crossover interactions were observed. For instance, 'Heritage', which usually had the lowest rank for yield, was the highest yielding cultivar in the Cambridge 1995 environment. This was also illustrated in Table 2 where the secondary effects for Cambridge 1995 were greater and positive compared to secondary effects for 1994 and 1996. 'Autumn Bliss' and 'Redwing' had greater G × E variance attributed to unpredictable elements contributing to the lower stability ranking.

Although 'Heritage' was more stable, it had the lowest primary effects indicating lower average yield compared to the other two cultivars. However, when combined with low yield, high stability is a negative term. 'Autumn Bliss' had the greatest primary effect and highest overall fruit yield (11.8 $kg \cdot m^{-2}$). In this study, 'Autumn Bliss' was the highest yielding cultivar in 11 of 17 environments. However, 'Autumn Bliss', although the best of all three cultivars, is not considered an ideal cultivar as defined by this model because the secondary effect scores (i.e., 4.02) indicated unpredictable GE interactions. The biplot analysis (Yan et al., 2000) does quantify GE interaction providing a useful statistic to assist the breeder in choosing between genotypes for parents or release as cultivars.

The strong interaction between genotype and environment for yield of PF raspberry was identified in several studies (Hoover et al., 1988; Keep, 1988; Privé et al., 1993a). In the Privé et al. (1993b) study, which is closely associated with these results, these three cultivars interacted with several climatic variables, most notably, soil temperature, water, and early fall air temperature. For instance, higher soil temperatures between April and October increased yields more for 'Redwing' and 'Heritage' than 'Autumn Bliss'. The amount of water received over the season affected yield and yield components of the three cultivars differently. Higher late-season air temperatures increased yield components (i.e., flowers per lateral) of 'Heritage' but had little influence on 'Autumn Bliss' and 'Redwing'. Cane density is a very important yield component in PF raspberry (Hoover et al., 1988; Privé et al., 1993a) and varies between years, locations and cultivars (Privé et al., 1993a). In this study, cane number per plot varied between years (data not reported). These four traits could all contribute to the GE interaction measured in this study. Trying to reduce GE interaction may not be practical or successful. In the Vineland 1989 and 1990 environments where the site was heavily irrigated both years, there was still a crossover interaction. Vegetative management to control cane density is not a viable option since high cane densities are required for high yields (Hoover et al., 1988). In the current study, there were some significant correlations between climatic variables and primary effects. To capitalize on these correlations, environments could be selected that differ in length of growing season and fall temperatures as a means to separate cultivars.

Although red raspberries have been widely tested, few studies have quantified the GE interactions. Fejer (1973) calculated the W statistic or ecovalence (Wricke, 1965) for several summer-bearing red raspberry cultivars and advanced selections grown at Ottawa, Ontario, Canada. The data were compiled over years in

Fig. 2. The GGE biplot for fruit yield based on 6 years (1991 to 1996) trial data from the Cambridge (C) location. PC 1 and PC 2 = primary and secondary effects, respectively.



one location on the same planting. Higher yield stability was closely linked to lack of injury to the overwintering cane. Winterhardiness is a low priority in PF raspberry, although some cultivars may be susceptible to root damage from low temperatures (Privé et al 1993a). The Cambridge location between the years 1991 and 1996 also represents a multi-year single location environment. The year × cultivar interaction was nonsignificant for fruit yield. When the years are presented in the biplot, 'Autumn Bliss' is the best adapted cultivar at Cambridge. Since winterhardiness is not a major concern in PF raspberry, testing may be done over a fewer number of years compared to summer-bearing raspberry. Locations may be a more important factor than years to include for testing of PF cultivars.

The biplot analysis (Yan et al., 2000, 2001) has been a useful tool to reclassify testing environments. Using multiple-environment data from winter wheat trials, Yan et al. (2000) were able to identify two mega-environments in Ontario where formerly five were believed to exist. This significantly reduced the testing effort for this crop while maintaining the quality of the data required for decision making. The current study was able to identify two mega-environments for PF raspberry, namely the 'Autumn Bliss' and 'Redwing' environments where each was the best performing cultivar. The two mega-environments encompass the individual environments (i.e., locations and years) above and below the line perpendicular to the line connecting 'Autumn Bliss' and 'Redwing' (Fig. 1). However, unlike the winter wheat study (Yan et al., 2000), the environments in this study, represent location and year combinations. Some locations and years occurred in both mega-environments making interpretation difficult. The 'Redwing' mega-environment included three different location and year combinations. Two environments, Harrow 1989 and Vineland 1990, were both in the longer season locations with the highest temperatures. Crossover interactions were also observed for 'Autumn Bliss' and 'Redwing' at Vineland and Harrow in 1989 and 1990. Crossover interactions decrease estimates of stability and make interpretation of multi-environment data difficult. Westcott (1986) illustrated that including or excluding a single extreme location could strongly influence stability estimates using the linear regression approaches to analyzing GE interaction. Excluding the short season New Liskeard environment had no effect on the overall interpretation of results.

In addition to information about the genotypes tested, the biplot can provide valuable information about testing environments. The best location to identify high- and stable-yielding genotypes should have large primary scores and near-zero secondary scores. Such an environment would be able to discriminate among genotypes and be representative of all environments (Yan et al., 2001). Those environments approaching these ideal values were Cambridge in 1989 and 1990, Harrow in 1990, Lavaltrie in 1990, and Vineland in 1989. With the exception of Lavaltrie, these locations have the longest growing seasons and represent the climatic areas where these cultivars can approach their full yield potential. The problem of testing in less than ideal environments is selecting genotypes with limited adaptability (because the test environments do not represent the broader region) and low stability. Previous studies (Hoover et al., 1988; Privé et al., 1993b) have shown that short season areas do not allow primocane-fruiting cultivars to reach their yield potential. 'Heritage' can be particularly disadvantaged because it matures later than the other two cultivars (Privé et al., 1993b).

Cultivar and advanced selection testing is a time and resource consuming activity in plant breeding. This is especially true in a perennial fruit crop such as PF raspberry which usually requires >2 years to reach full productivity and several years of evaluation. Optimizing resources used for testing can save time and money while still providing the data necessary for making critical decisions in a breeding program. The biplot analysis (Yan et al., 2000) used in this study assisted the evaluation process by quantifying stability for the cultivars, identifying redundant environments by establishing mega-environments, and identifying the most productive cultivars.

Literature Cited

Dale, A. and Daubeny, H. 1985. Genotype–environment interactions involving British and Pacific Northwest red raspberry cultivars. HortScience 20:68–69.

Fejer, S. 1973. Genotype × year interactions and ecovalence in raspberry selections. Can. J. Genet. Cytol. 15:226–229.

Fiola, J. 1999. The cooperative MD/NJ/VA/WI bramble beeding program. Proc. N. Amer. Bramble Growers Assn. Conf., Orlando, Fla., 11–12 Feb.

Gauch, H.G. and R.W. Zobel. 1997. Identifying mega-environments and targeting genotypes. Crop Sci. 37:311–326.

Hoover, E., J. Luby, D. Bedford, and M. Pritts. 1988. Vegetative and reproductive yield components of primocane-fruiting red raspberry. J. Amer. Soc. Hort. Sci. 113:824–826

Keep, E. 1988. Primocane (autumn)-fruiting raspberries: A review with particular reference to progress in breeding. J. Hort. Sci. 63:1–18.

Mandel, J. 1961. Non-additivity in two-way analysis of variance. Amer. Stat. Assn. J. 65:878–888.

Privé, J.P., J.A. Sullivan, J.T.A. Proctor, and O.B. Allen. 1993a. Performance of three primocane-fruiting red raspberry cultivars in Ontario and Quebec. J. Amer. Soc. Hort. Sci. 118:388–392.

Privé, J.P., J.A. Sullivan, J.T.A. Proctor, and O.B. Allen. 1993b. Climate influences vegetative and reproductive components of primocane-fruiting red raspberry cultivars. J. Amer. Soc. Hort. Sci. 118:393–399.

SAS, 1999. Version 8. SAS Inst., Inc., Cary, N.C.

Sullivan, J.A. and J.P. Privé. 2001. Yield stability indices of primocane-fruiting red raspberry (*Rubus idaeus* L.). Can. J. Plant Sci. 81:297–301.

Westcott, B. 1986. Some methods of analysing genotype–environment interaction. Heredity 56:243–253.

Wricke, 1965. Ueber eine biometrische Methode zur Erfassung der oekologischen Anpassung. Acta Agr. Scand. (Suppl.) 16:98–101.

Yan, W. 2001. GGE biplot—A windows application for graphical analysis of multi-environment trial data and other types of two-way data. Agron. J. 93:1111–1118.

Yan, W., P.L. Cornelius, J Crossa, and L.A. Hunt. 2001. Comparison of two types of GGE biplots in genotype by environment interaction analysis. Crop Sci. 41:656–663.

Yan, W. and L.A. Hunt. 1998. Genotype by environment interaction and crop yield. Plant Breeding Rev. 16:135–178.

Yan, W. and L.A. Hunt. 2001. Genetic and environmental causes of genotype by environment interaction for winter wheat yield in Ontario. Crop Sci. 41:19–25.

Yan, W., L.A. Hunt, Q. Sheng, and Z. Szlavnics. 2000. Cultivar evaluation and mega-environment investigation based on the GGE biplot. Crop Sci. 40:597–605.