STABILITY INDICES FOR HORTICULTURAL CROPS
Analysis of Genotype by Environment Interactions

The average yield of a genotype (i.e., species or cultivar) measured over several years and/or at several locations has been used as a measure of crop performance and adaptation in different environments. While an average yield is one indicator of performance, it does not explain the underlying basis for that performance. For example, an average yield may be due to similar yields over several years and/or at several locations, or it may be due to a combination of extremely high and low yields. Conclusions about adaptability or yield stability would be quite different in each case. In many instances stable yields may be as important as average performance. For example, stable production may be more desirable than high, but inconsistent, yields that interfere with marketing.

A measure of stability would be helpful to improve cultivar recommendations to growers. Several procedures have been developed to assess stability. Mostly, these procedures have been used by plant breeders to evaluate the stability of yield of different genotypes, but these procedures also could be used by horticulturists for evaluating horticultural traits. Although used to a limited extent by horticulturists, several studies have been reported:

Crop	Traits measured
Apple rootstocks	Tree size, yield, yield efficiency
Blueberry	Yield
Carrots	Yield, split roots, purple-topped roots
Muskmelon	Yield components, soluble solids
Onions	Yield, winter kill, bolting, maturity
Peas	Yield components, days to flower, growth habit
Strawberry	Yield
Sweet potato	Yield, leaf scab incidence
Tomato	Yield, soluble solids, citric acid content

For the specific reference for each crop, except apple, see Pritts and Luby (1990). The apple references are cited below.

Stability can be defined as low variation in a particular trait when measured over numerous locations and/or years. Standard statistical methods are used to compare the variation of several genotypes across environments (i.e., locations and/or years). These statistical methods include: 1) coefficients of variation, 2) analysis of variance, 3) linear regression, and 4) deviations from regression (Pritts & Luby 1990). To illustrate how to calculate a stability index, an example using a regression approach to evaluate the performance and stability of tree growth and yield of different apple rootstocks will be demonstrated.

When using regression to evaluate phenotypic stability, two variables must be plotted: 1) a measure of the environment at each site (i.e., independent variable) and 2) the resulting phenotypic response of each genotype at each site (i.e., dependent variable). Since it is not practical, and often not possible, to precisely quantify the environmental characteristics (e.g., temperature, soil water, light, etc.) that contribute to the trait being evaluated, the average performance of all genotypes at each site is used as an environmental (or site) index for that site. Then, the specific phenotypic response of each genotype at each site is regressed against the environmental index for its respective site. After linear regression equations are calculated for each genotype, the regression coefficient (i.e., slope of the linear regression line or β) of each genotype can be compared to the overall average performance of all genotypes as a measure of its stability. The average regression coefficient for all genotypes always equals 1.0, so genotypes with $\beta<1.0$ (i.e., flatter slopes) are considered more stable than the average genotype, while genotypes with $\beta>1.0$ (i.e., steeper slopes) are considered less stable. Therefore, a more stable genotype is less responsive to changes in the environment than a less stable genotype. Sometimes the more stable genotype performs better than the less stable genotype under poor environmental conditions, but not as well under better conditions. An ideal genotype would perform better than most others in poor environments, while still performing well in good environments.

In 1980, a trial that included nine apple rootstock cultivars (MAC.24, OAR 1, M.7 EMLA, M.26 EMLA, O.3, M.9 EMLA, M.9, MAC.9, and M.27 EMLA) with 'Starkspur Supreme Delicious' as scion was planted at numerous sites across North America. The EMLA (i.e., East Malling-Long Ashton) rootstocks are certified virus free. Ten replications of each rootstock were planted at 3.5 x 5.5 m spacing at each site. Trees were trained to a central leader system with cultural practices applied according to local recommendations. Half of the replications in each planting were un-staked and half were supported by single post. The performance of these rootstocks was evaluated over 10 years (NC-140 1991).

Cultivar evaluations of perennial plants are usually conducted at a single site because of the intensive, long-term management requirements associated with such trials. So, while environmental differences at different sites have been observed, they have rarely been quantified. It is often assumed that the relative ranking of cultivars for a variety of traits would not change across a range of poor-to-good growing sites (i.e., no G x E interaction).

With the data from the NC-140 trial, Olien *et al.* (1991) used linear regression analysis to calculate stability indices for cumulative tree size (measured as trunk cross-sectional area [TCSA] in cm^2), cumulative yield (kg/tree), and cumulative yield efficiency (kg/cm^2 TCSA). Yield efficiency is often used to evaluate the yield performance of fruit trees because it compensates for differences in tree size, since bigger trees usually produce higher yields than smaller trees. They used cumulative responses over the 10-year period rather than annual responses because cumulative responses are more relevant to long-term orchard productivity and economic potential. Cumulative responses also are more stable than annual ones because they integrate differences in environmental conditions (e.g., winter injury) and cultural practices (e.g., irrigation), and annual variations in yield caused by biennial bearing or differences in rootstock precocity at each site.

The phenotypic responses (i.e., cumulative yield, cumulative tree size, or cumulative yield efficiency) of each cultivar at each site were plotted and regressed against each respective site's environmental index (i.e., average performance of all rootstocks at each site). The data used and the regression analyses are shown in the following table:

	Environmental Index			Yield (kg/tree)			Trunk cross-sectional area, TCSA (cm^2)			Yield efficiency, YE (kg/cm^2 TCSA)		
Site	Yield	TCSA	YE	M.7 EMLA	M.9 EMLA	M.9	M.7 EMLA	M.9 EMLA	M.9	M.7 EMLA	M.9 EMLA	M.9
California	374	82	5.5	440.4	92.0	130.3	69.1	53.1	18.0	6.41	3.79	7.24
Ontario	255	83	3.7	383.2	298.8	165.0	122.8	58.7	37.7	3.11	4.98	4.37
Oregon	202	61	3.8	370.2	154.3	130.3	105.7	40.0	37.5	3.57	3.88	4.12
Wisconsin	192	65	3.5	284.9	183.5	126.3	87.3	40.2	26.9	3.23	4.38	4.66
Indiana	166	85	3.9	230.1	223.0	104.0	132.2	60.6	27.5	1.61	3.99	4.34
Massachusetts	165	35	5.2	282.3	158.5	76.9	69.5	23.3	14.0	4.03	6.76	5.48
Ohio	158	58	3.5	214.3	172.3	97.7	73.3	41.1	22.5	2.93	4.16	4.28
Virginia	146	79	2.8	190.0	136.3	108.2	137.4	51.6	35.8	1.45	3.63	3.97
Georgia	136	96	1.7	125.4	64.3	41.0	142.1	38.3	22.5	1.68	1.72	1.81
Illinois	118	87	2.2	105.0	172.9	109.9	95.8	46.5	34.3	1.30	3.70	3.14
Kentucky	95	63	1.9	145.4	113.7	86.5	72.9	39.3	42.4	1.97	2.89	2.34
Michigan	76	50	2.1	98.6	86.3	71.7	78.7	31.8	25.1	1.28	2.77	2.87
Iowa	74	62	1.4	89.2	75.2	77.4	97.3	48.5	42.4	0.89	1.45	1.81
Arkansas	71	64	1.2	99.8	89.4	69.0	85.6	51.2	45.0	1.18	1.77	1.57
Washington	55	34	1.9	108.2	31.0	24.8	45.1	13.2	10.2	2.35	2.34	1.85
Pennsylvania	46	45	1.8	69.7	59.7	38.8	69.7	27.1	23.5	1.67	3.75	1.60
Quebec	31	37	1.2	33.4	40.1	29.7	62.0	23.3	18.4	0.55	1.83	1.57
AVERAGE	139	64	2.8	192.4	126.6	87.5	91.0	40.5	28.4	2.31	3.40	3.35
Slope (stability)				1.33	0.44	0.36	1.16	0.56	0.23	0.94	0.83	1.18
Intercept				8.24	65.4	37.7	16.8	4.47	13.9	–0.30	1.09	0.07
R^2				0.89	0.29	0.61	0.62	0.67	0.18	0.75	0.66	0.93

Questions:

- What conclusions can be made about the performance and stability of these rootstocks for the traits that were measured?
- What aspect(s) of the environment might account for the differences in the phenotypic responses of these genotypes?

One of the primary conclusions of the research by Olien *et al*. (1991) was that the "relative ranking of rootstocks should not be expected to be constant across growing sites" (Olien *et al*. 1995). One of the main limitations of the regression approach for calculating stability indices is that the results of the trial cannot be extended to predict performance at sites that were not included in the original trial, because the specific aspect(s) of the environment that account for differences in the environmental index are unknown at untested sites, and, therefore, an environmental index cannot be calculated. If, however, some aspect(s) of the environment at the test sites could be correlated with each site's respective environmental index, then an environmental index could be calculated for an untested site and the expected tree performance could be estimated. Olien *et al*. (1995) performed this type of analysis using environmental data taken during the NC-140 rootstock trial. During preliminary analyses, they found that the mean daily maximum temperature and the total moisture received (i.e., precipitation plus irrigation) at each site were better predictors of expected cumulative yields at each site than were monthly average and extreme minimum temperatures and total monthly solar radiation. They analyzed mean daily maximum temperatures (TEMP_{max}) and total moisture ($\text{MOIST}_{\text{total}}$) over five annual developmental stages of apple. These periods and the correlation coefficients (r) of TEMP_{max} and $\text{MOIST}_{\text{total}}$ against site index for cumulative yield at ten test sites (AR, IL, IW, KS, MA, OH, OR, PA, VA, and WI) are shown in the following table:

		Correlation coefficients	
Monthly period	Developmental stage	TEMP_{max}	$\text{MOIST}_{\text{total}}$
Dec.-Jan.	Dormancy	–0.20 ns	+0.23 ns
Feb.-Apr.	Late winter to prebloom	–0.45 ns	–0.04 ns
May-June	Bloom through fruit set	–0.88	–0.85
July-Sept.	Fruit growth to harvest	–0.79	–0.43 ns
Oct.-Nov.	Postharvest to leaf fall	–0.59 ns	–0.07 ns

ns = Non-significant at the 5% probability level.
$\text{MOIST}_{\text{total}}$ was not measured at PA.

Only in the bloom to harvest periods was TEMP_{max} significantly correlated with cumulative yield; and only in the bloom through fruit set period was $\text{MOIST}_{\text{total}}$ significantly correlated with cumulative yield. In addition, it was found that TEMP_{max} and $\text{MOIST}_{\text{total}}$ during May-June were significantly collinear (r = 0.64).

Questions:

- What does this analysis suggest about the effects of temperature on cumulative yields of apple trees?

- How could this method be used to predict the performance of a cultivar at a site that was not included in a trial?

A subsequent NC-140 apple rootstock trial was conducted from 1984-93. This trial included 15 rootstocks (but not M.9 EMLA or M.9) at 29 sites throughout North America (NC-140, 1996). Olien *et al*. (1996) analyzed the stability and performance of these rootstocks as they did for the 1980-89 rootstock trial. In contrast to the earlier study, they generally found that greater stability across sites was correlated with lower genotype performance at the average site. In other words, unlike M.9 EMLA in the 1980-89 trial, no rootstock in the 1984-93 trial showed improvements in both stability and performance for cumulative yield, tree growth, or yield efficiency.

Literature Cited

NC-140. 1991. Performance of 'Starkspur Supreme Delicious' on 9 rootstocks over 10 years in the NC-140 cooperative planting. Fruit Varieties J 45(4): 192-199.

NC-140. 1996. Performance of the NC-140 cooperative apple rootstock planting: I. Survival, tree size, yield and fruit size. Fruit Varieties J 50(1): 6-11.

Olien WC, Ferree DC, Bishop BL. 1996. Performance potential and stability of 15 apple rootstocks as affected by North American growing sites over the period 1984-1993. Fruit Varieties J 50(1): 62-68.

Olien WC, Ferree DC, Bishop BL, Bridges Jr. WC. 1995. Prediction of site index and apple rootstock performance from environmental variables. Fruit Varieties J 49(3): 179-189.

Olien WC, Ferree DC, Bishop BL. 1991. Long-term performance potential and stability across 10 environments for nine apple rootstocks tested in the 1980-81 NC-140 trial. Fruit Varieties J 45(4): 208-212.

Pritts M, Luby J. 1990. Stability indices for horticultural crops. HortScience 25(7): 740-745.

1/13/2006