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Power Analysis of On-farm Fertilizer Trials with Tomato

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With the development of best management practices for vegetables grown in Florida, fertilizer recommendations try to balance profitability with environmental stewardship. When analysis of variance fails to reject the null hypothesis in two-rate fertilizer trials, power analysis should be used to determine the level of risk taken in accepting the null hypothesis that yields are the same with the two rates. Analysis of variance of yield components of five on-farm tomato (*Solanum lycopersicum* L.) trials found significant differences 25% and 36% of the time for single grade and cumulative yields, respectively. Single grade and cumulative yield variances were 75% and 15% of the time <5 25-lb boxes/acre, respectively. For cumulative yields, 80% of variances were 5 to 15 25-lb boxes/acre. Retrospective power analysis showed power overall ranged between 0.20 and 0.66 when variance was 5 to 10 25-lb boxes/acre, and when four replications and an economical yield difference of 10 25-lb boxes/acre were used. Under current field conditions (four replications, variance between 0 and 20 25-lb boxes/acre), a difference of 50 25-lb boxes/acre may be detected with a power of 0.80. Prospective power analysis showed that power may be increased to at least 0.80 when a yield difference of 50 25-lb boxes/acre and a variance <20 25-lb boxes/acre are used or when the number of replications is increased to six and the variance is <5 25-lb boxes/acre. Further discussion and consensus are needed to identify a power value that well balances type I and type II risks in fertilizer trials.

Detailed fertilizer recommendations are available for all the major vegetable crops grown in Florida (Hochmuth and Hanlon, 2000a, 2000b; Hochmuth et al., 2003a, 2003b; Olson and Simonne, 2006). These fertilizer recommendations were derived from regression equations that describe actual yield or relative yield responses to fertilizer rate in trials conducted in fields with low concentration of the element of interest (Evans, 1987). For examples of yield response to N rates, see Locascio et al. (1996) and Rhodes et al. (1988) for drip-irrigated and Hochmuth et al. (1989) for seepage-irrigated tomato. While the quadratic polynomial model has been commonly used, the linear plateau and quadratic plateau models may also be justified in describing yield responses to fertilizer rates (Abdul-Baki et al., 1997; Cerrato and Blackmer, 1990; Hochmuth et al., 1993a, 1993b; Sanchez et al., 1991; Willcutts et al., 1998). Equation parameters may be estimated with SAS using PROC REG for the quadratic polynomial model and PROC NLIN for the linear plateau and quadratic plateau models (SAS, 2002). The optimal fertilizer rate is the rate that corresponds to the maximum yield (calculated by solving the equation that describes the first derivative of the yield function equal to zero) for the quadratic polynomial model, or to the shoulder point for the linear and quadratic plateau functions (Frageria et al., 1997). Much importance has been given to comparing the optimal rates achieved using different models for crops such as corn (*Zea mays* L.; Cerrato and Blackmer, 1990) and lettuce (*Lactuca sativa* L.; Willcutts et al., 1998). It is commonly accepted that when the same data set is analyzed with these three models, increasing fit (measured by adjusted R^2 values) is obtained with the quadratic polynomial, linear plateau and quadratic plateau models. Also, the linear plateau, quadratic plateau, and quadratic polynomial generate optimal rates of increasing value (Abdul-Baki et al., 1997; Cerrato and Blackmer, 1990; Willcutts et al., 1998). Hence, although no consensus exists about which model should be used, the selection of the optimal rate somewhat depends on the equation used.

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The development and adoption of the best management practice (BMP) program for vegetable crops grown in Florida has placed a new emphasis on fertilizer recommendations (FDACS, 2006; Simonne and Ozores-Hampton, 2006) and on the on-farm demonstration of the effect of fertilizer rates on crop yield (Hochmuth et al., 2003c; Ozores-Hampton et al., 2006). On-farm trials have the advantage of better representing field conditions and they should be used to validate small-plot research results (Cantliffe et al., 2006). However, on-farm trials may interfere with normal farming operations and hence, may include fewer rates and use larger plots. Using tomato as an example, factors such as field heterogeneity, large plots, and different picking crews used at each harvest may increase the variability of yield data from field trials. Moreover, when seepage irrigation is used, the independence of each plot may be affected by plot-to-plot nutrient movement due to a temporary rising of the water table caused by leaching rains or frost protection events.

When two fertilizer rates are compared in on-farm trials, these rates are often the grower's rate and the UF–IFAS recommended rate. On one hand, the cooperating grower expects to see a higher yield with his/her rate. Statistically, this corresponds to expecting to reject the null hypothesis that "yields are the same with both nutrient rates." On the other hand, the researcher expects to validate the UF–IFAS rate and to show that yields are similar with both rates. With BMPs in mind, the researcher is trying to demonstrate that comparable yields may be achieved with a reduced rate thereby reducing the risk of environmental impact. Statistically, this corresponds to expect to accept the null hypothesis. These two expectations in decision making are controlled by two different types of risk. The statistical risk of rejecting a true null hypothesis is controlled by α, the type I error (also called level of significance). The risk of accepting a false null hypothesis is controlled by β, the type II error. Hence, α represents the risk of a "false discovery" (finding differences when there are none) whereas β represents the risk of "missing a real difference." Power (calculated as $1 - \beta$) is the probability of rejecting a false null hypothesis. Because a study has a $1 - \beta$ probability of detecting a significant treatment effect equal to the effect size at the α risk (Lenth, 2001), high power is desirable in fertilizer trials. Two types of power analysis exist. In retrospective power analysis, the power of an experiment is calculated after conducting the experiment, using the observed effect size, sample size and variance when the analysis of variance failed to reject the null hypothesis (P value$> \alpha$). Prospective power analysis conducted before an experiment (and in the absence of preliminary data) follows a logical assessment of what constitutes an important effect. Several software packages including SAS are now available to calculate power or sample size (Thomas and Krebs, 1997; Goldstein, 1989; High, 2006).

While the statistical analyses of social sciences and clinical trials routinely report type II error (Cohen 1988; Cortina and Nouri, 2000), traditional horticultural research does not. This is because the expectations of the researcher are typically to reject a false null hypothesis without any interest in knowing the risk taken when it is accepted (the power is always assumed to be high). However, this assumption is not always true (Cohen, 1988). Growers, researchers and policy makers involved in nutrient management and BMP issues should know the level of confidence (or the risk taken) when declaring that yields obtained with two fertilizer rates are "the same." Therefore, the objectives of this study were to conduct retrospective and prospective power analyses of published results from on-farm trials with tomato (Ozores-Hampton et al., 2006) and determine the number of replications needed for each trial to achieve a power of 0.80.

Materials and Methods

The power statistics associated with pairwise comparisons (fertilizer trials with two N rates) were calculated using PROC POWER (SAS, 2002; Table 1). Input parameters into the power calculation are sample size (n), type I error (α), and effect size (d). A sample size of n=8 was calculated by multiplying number of treatments (2) by the number of replications (4). The conventional value of 0.05 was used for α. The specification of d is usually the most difficult input for a power analysis (High, 2006). The effect size is calculated as $d = \mu_A - \mu_B/\sigma$, where μ_A and μ_B are the group means and σ is the standard deviation (Cohen, 1988). In two-rate fertilizer trials, $\mu_A - \mu_B$ represents the smallest yield difference that the experimenter wished to detect. In the absence of widely accepted value, this difference may be selected arbitrarily. For example, differences in tomato yields of 10, 25, 100, 250, or 400 25-lb boxes/acre, which represent 0.4%, 1%, 4%, 10%, and 20% of a typical 2500 25-lb boxes/acre yield, respectively, may be arbitrarily selected. As an alternative, this paper defined $\mu_A - \mu_B$ as the minimum yield increase from the higher N rate needed to offset the higher fertilization cost. From an economical standpoint, the smallest effect size of importance is represented by the yield increase needed to offset the cost of the fertilizer rate

Table 1. SAS codes used for power calculations with PROC POWER.[z]

SAS codes	Comments
PROC POWER;	
twosamplemeans	This is a single SAS statement; no comma until the end
alpha=0.05	
sides=2	2-group comparison
meandiff = A B C D	Multiple group mean differences may be specified in one run
stddev= a b c d	Multiple standard deviations may be specified in one run
npergroup=4	Replications per group
power=.;	What SAS calculates
plot X=power min=2	New statement that plots the power curve
max=50	
key=bycurve(numbers=	
off pos=inset);	
run;	

[z] Proc power also allows the calculation of the number of observations for preset values of variance and power.

Table 2. Summary of yield differences, significance, coefficient of variation, and variance estimate for tomato marketable yields from on-farm trials conducted in South Florida in the 2005–2006 growing season (from Ozores-Hampton et al., 2006).

Trial No.[z]	Parameter	Extra large (XL)[v]			Large (L)			Medium (M)			Total[u]						
		1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	XL	L	M	1	2	3	All[t]
		Column number															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
4	200 and 260 (lbs of N/A)																
	Yield difference[y] (25 lb-box/A)	- 28	33	3	-22	2	18	6	-41	117	8	-2	82	-44	-6	138	88
	Significance[x]	0.73	0.49	0.94	0.42	0.99	**0.02**	0.74	0.35	**0.02**	0.94	0.26	0.37	0.56	0.94	**0.01**	0.22
	CV (%)[w]	18	15	33	13	15	15	36	28	27	13	7	25	10	12	13	6
	RMSE[s]	8.1	4.6	4.7	12.8	5.1	2.9	1.9	4.2	4.0	11.8	5.1	8.7	7.2	9.5	6.4	11.5
5	200 and 300 (lbs of N/A)																
	Yield difference (25 lb-box/A)	-140	-39	29	-20	14	29	11	24	98	-150	23	133	-149	-1	156	6
	Significance	**0.01**	0.11	0.13	0.29	0.57	0.11	0.41	0.35	**0.01**	**0.02**	0.55	**0.02**	**0.02**	0.96	**0.01**	0.94
	CV (%)	24	21	53	19	28	43	37	34	29	17	17	19	18	15	30	12
	RMSE	7.2	3.8	3.0	3.0	4.1	2.8	2.2	4.1	3.9	9.0	6.5	5.9	9.2	6.5	7.4	14.0
6	200 and 330 (lbs of N/A)																
	Yield difference (25-lb box/A)	-9	16	-12	-21	6	27	18	40	-8	-5	0	50	-12	62	7	57
	Significance	0.87	0.62	0.56	0.42	0.86	0.51	0.36	0.14	0.84	0.93	0.89	0.39	0.87	0.40	0.92	0.74
	CV (%)	28	44	41	15	26	24	32	18	15	21	17	13	18	21	14	13
	RMSE	6.7	3.6	2.5	3.1	4.0	4.6	1.8	2.8	4.4	8.1	9.4	6.5	9.0	8.2	7.9	18.9
7	200 and 320 (lbs of N/A)																
	Yield difference (25-lb box/A)	131	-44	110	97	76	116	8	-12	86	197	289	112	236	20	212	468
	Significance	0.62	0.62	**0.01**	**0.04**	**0.04**	**0.01**	0.51	0.51	**0.01**	0.41	**0.01**	**0.01**	**0.01**	0.48	**0.01**	**0.01**
	CV (%)	7	21	16	19	19	15	49	49	13	8	16	12	4	13	8	4
	RMSE	7.8	11.1	2.2	5.0	5.0	2.9	1.6	1.6	1.9	14.2	11.6	2.5	5.0	10.9	4.0	10.6
8	200 and 260 (lbs of N/A)																
	Yield difference (25-lb box/A)	-212	-158	-10	59	-7	-16	16	61	-7	-380	36	70	-137	-104	-33	-274
	Significance	0.10	**0.02**	0.70	0.18	0.90	0.16	0.06	**0.01**	0.98	**0.02**	0.09	**0.05**	0.40	0.31	0.60	0.09
	CV (%)	27	19	58	28	21	38	58	31	35	18	8	22	27	14	29	10
	RMSE	12.3	5.1	1.1	4.5	4.3	0.9	0.85	1.6	2.8	13.1	3.0	3.3	16.8	7.3	3.6	12.5

[z] Trial 5 was drip-irrigated and others were seepage irrigated.

[y] Algebraic yield difference (in 25-lb box/acre) calculated by difference between the yield obtained with the high rate (grower's) and the low (UF–IFAS) rate.

[x] Significance is the *P* value of the N rate term in the ANOVA table; *P* values <0.05 are in bold.

[w] CV (%) = coefficient of variation = 100 × grand mean/sqrt-MSE; MSE = Mean Square error from ANOVA table; sqrt = square root.

[v] Extra large (XL), large (L) and medium (M) represent USDA tomato grades; 1st, 2nd and 3rd represent the tomato harvests.

[u] Total yields calculated by adding yields for the three harvests for the XL, L, and M grades, and by adding yields for the three grades for the 1st, 2nd, and 3rd harvests.

[t] Cumulative marketable yield for all grades and harvests.

[s] RMSE = square root of the Mean Square Error term in the ANOVA.

used by the grower rate in excess of the recommended rate. Most trials conducted by Ozores-Hampton et al. (2006) included a 100 lbs/acre difference between the two N rates (Table 2). Given the current prices of $0.40/lbs of N (or $40/acre cost for the extra 100 lbs/acre of N fertilizer used), it would take a yield increase of 2 to 10 25-lb boxes/acre to make up that cost when market prices range from $20 to $4/box. Hence, selecting $\mu_A - \mu_B$ as being equal to 10 25-lbs box/acre, represents the economic threshold around which a grower would base his or her N-rate fertilization decision. It should be noted that the value selected for $\mu_A - \mu_B$ does not affect the level of significance (α), and therefore does not affect the results of the analysis of variance.

The determination of d also requires an estimation of σ. In retrospective power analysis, the square root of the mean square error terms (RMSE) from the analysis of variance tables provided by PROC GLM were used as an estimate of σ (Table 2). Because three USDA grades exist for tomato and three harvests were performed in these five trials, a total of 45 grade category × harvest number variances were available (45 = 3 × 3 × 5). The numbers of variance for grade category x harvest number in the 0–5, 5–10, and 10–15 25-lb boxes/acre variance group ranges were 34, 8, and 3 respectively. Hence, in these field trials, the variance of each grade category × harvest fell 75%, 18%, and 7% in the 0–5, 5–10, and 10–15 25-lb boxes/acre variance group, respectively. This variance distribution shows that the most common value for variance in this group of field trials was between 0 and 5 25-lb boxes/acre (75% of the occurrence), but was greater than 5 25-lb boxes/acre in 25% of the occurrences. Cumulative yields are often calculated in fertilizer trials to facilitate comparisons among trials. Hence, for each trial, individual grade category × harvest number were cumulated to calculate seasonal yields in extra-large (XL), large (L), and medium (M) categories and total marketable yields for harvests 1, 2, and 3. In addition, the 35 (5 trials × 7 cumulative grades) season total marketable yields and their variances were also calculated. The number of variances of cumulative yield categories, was 5 (14%), 12 (34%), 16 (46%), and 2 (6%) in the 0–5, 5–10, 10–15, and 15–20 25-lb boxes/acre variance groups, respectively. Cumulative variances were greater than 5 25-lb boxes/acre 86% of the occurrences (and greater than single-grade variances) and the most frequent variance of cumulative grades was 10–15 25-lb boxes/acre. Based on these observations, variance values of 5, 10, 15, and 20 were selected for power analysis. Finally, using the variance distribution from Ozores-Hampton et al. (2006), a prospective power analysis was performed to determine the sample size needed to detect yield differences between 10 and 400 25-lb boxes/acre with a power of 0.80. The selection of the 0.80 value for power is arbitrary as no historical or consensus value exists in horticultural research. Nevertheless, it was selected because it is the accepted value in social and medical research. This value of 0.80 for power means that the probability of rejecting a false null hypothesis is 0.80, or that we accept a 20% risk of missing a real difference among treatment effect.

Results and Discussion

Significant differences ($P < 0.05$) among fertilizer rates were detected by analysis of variance 11 out of 45 times (or 25%) for columns 3–11 and 12 out of 35 times (or 34%) for columns 12–18 (Table 2). The corresponding yield differences were negative (low N rate significantly producing greater yield than the high N rate) 2 times (in trials 5 and 8) and 3 times (2 in trial 5 and once in trial 8) for single-grade and cumulative yield categories, respectively. Hence, 45% (5 out of 11) of significant differences showed a higher yield with the low N rate. Significant differences were found once for most grade , harvest combination and 2 and 3 times for large third-harvest and medium third-harvest grades, respectively. Significant differences were found in 3 out 5 trials for the cumulative medium and third-harvest categories. These result suggested that the benefit of using the high N rate on tomato yield (55% or 6 times out of 11) was statistically detected mostly at the third harvest for the medium grade. Hence, the need for power analysis was justified a posteriori because the analysis of variance failed to reject the null hypothesis 75% and 64% of the time for columns 3–11 and 12–18, respectively (Table 2).

Power curves showed that a power of 0.80 was achieved with a sample size of 6, 18, 38, and >50 for standard deviation values of 5, 10, 15, and 20 25-lb boxes/acre and an economical yield difference of 10 25-lb boxes/acre (Fig. 1). These results suggest that a power of 0.80 cannot be achieved with that yield difference and the classical 4 replications used in field research when variance exceeds 5 25-lb boxes/acre (a variance >5 25-lb boxes/acre was observed in 25% and 52% of the grade and cumulative grades, respectively). Hence, the typical design of fertilizer trials

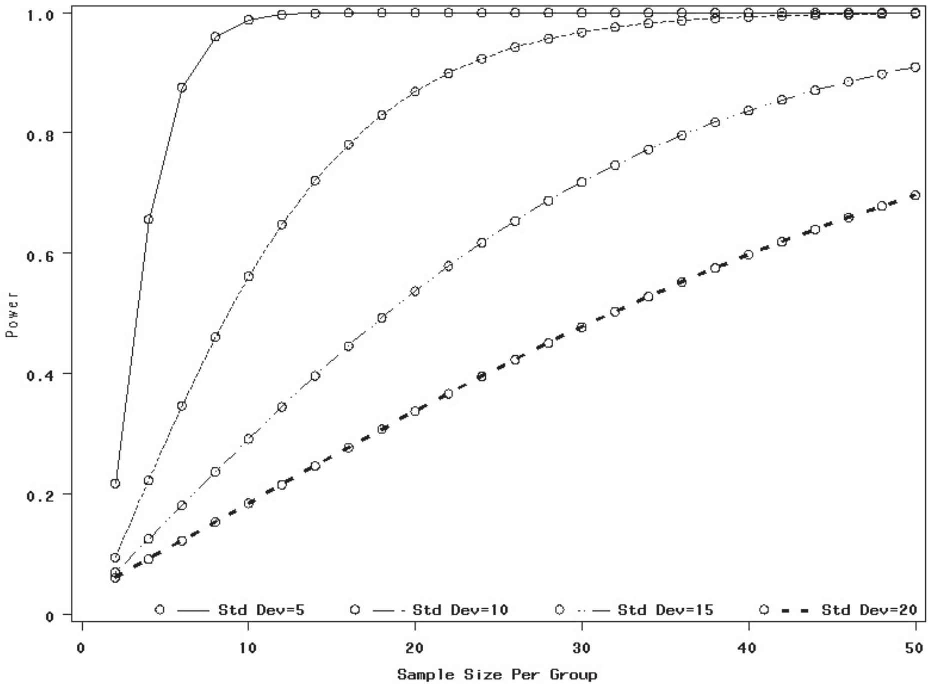

Fig. 1. Sample power curves generated by PROC POWER showing power response to sample size for variance values of 5, 10, 15, and 20 25-lbs boxes/acre and for a yield difference of 10 25-lb boxes/acre.

Table 3. Calculated power values for four replicates ($n = 4$), $\alpha = 0.05$, and different variances and yield differences using SAS PROC POWER (data from Ozores-Hampton et al., 2006).[z]

Variance (25-lb	Yield difference (25-lb boxes/acre)					
boxes/acre)	10	20	30	40	50	75
5	0.66	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**
10	0.22	0.66	**0.94**	**0.99**	**0.99**	**0.99**
15	0.13	0.36	0.66	**0.88**	**0.98**	**0.99**
20	0.09	0.22	0.43	0.66	**0.84**	**0.99**
50	0.06	0.08	0.11	0.16	0.22	0.43
100	0.06	0.06	0.07	0.08	0.09	0.15
200	0.05	0.05	0.05	0.06	0.06	0.07

[z] Power values >0.80 are in bold.

Table 4. Number of replicates needed to achieve a power of at least 0.8 for variance values ranging from 5 to 200 25-lb boxes/acre and yield differences ranging from 10 to 400 25-lb boxes/acre using SAS PROC POWER.[z]

Variance (25-lb	Yield difference (25-lb boxes/acre)								
boxes/acre)	10	20	30	40	50	75	100	200	400
5	6	**3**	**2**	**2**	**2**	**2**	**2**	**2**	**2**
10	17	6	**4**	**3**	**3**	**2**	**2**	**2**	**2**
20	64	17	9	6	**4**	**3**	**3**	**2**	**2**
50	394	100	45	26	17	9	6	**3**	**2**
100	1571	394	176	100	64	29	17	6	3
200	6281	1571	699	394	253	113	64	17	6

[z] Sample sizes of four or smaller are in bold.

with four replications and a variance in the range of 0–20 25-lb boxes/acre is not adequate to conclude with a 0.80 confidence that two N rates statistically produced similar yields. When four replications were used, power was 0.70 when the variance was 5 25-lb boxes/acre, but was less than 0.40 when the variance ranged between 10 and 20 25-lb boxes/acre (Fig.1). A power of 0.40 means that these analyses of variances had 6 out 10 of chances to miss a true treatment effect. When four replications are used, a power of 0.80 may be achieved with yield differences of 30, 40, and 50 25-lb boxes/acre for variance values of 10, 15, and 20 25-lb boxes/acre, respectively (Table 3). These results indicate that a power of <0.80 exists when a conclusion that fertilizer rates have so effect on yield in fertilizer trials conducted with four replications and having a variance <10 25-lb boxes/acre. The actual number of replications needed to achieve a 0.80 power for variances ranging from 5 to 200 25-lb boxes/acre and yield differences ranging from 10 to 400 25-lb boxes/acre are shown in Table 4. A yield difference of 50 25-lb boxes/acre may be detected with four replications with a variance ranging between 5 and 20 25-lb boxes/acre with a power of 0.80, but power was always less than 0.66 for all variance when the yield difference was only 10 25-lb boxes/acre (Table 3). This result indicates that under the current experimental designs (with four replications), 50 25-lb boxes/acre is the smallest yield difference for which a power of 0.80 can be achieved when the variance equals 20 25-lb boxes/acre. Under current fertilizer prices, such a high number of boxes for the economical threshold would imply a market value near $1/box ($40/50), which is well below break-even point. Conversely, the fertilizer cost needed for 50 25-lbs boxes/acre to be the economical threshold under a market value of $8/box would be $400/acre (50 25-lb box/acre × $8/box) for 100 lbs/acre of N. Hence, if the cost of N fertilizer increased 10 fold (from $0.40 to $4 per lb of N), 50 25-lb box/acre would become the new economical threshold. It is unlikely that this will happen in the near future.

Power may be increased by increasing the number of replications. While it is relatively easy to increase sample size in social science studies (by increasing the number of survey respondents for example), data collection in field trials is costly and time-consuming, making large number of replications (>20) unpractical. Increasing field replications to 6 (by considering 6 as the greatest practical number of replication for field trials), yield differences of 10, 20, and 40 25-lb boxes/acre may be declared statistically similar with variance values of 5, 10, and 20 25-lb boxes/acre, respectively (Table 4). A yield difference of 10 25-lb boxes/acre may only be detected with a 0.80 power with 6 replications when variance is 5 25-lb boxes/acre. It is therefore essential to keep variance low if a power of 0.80 is to be achieved in the field when six replications are used. However, most factors contributing to field variability (soil characteristics within a field, fruit set, disease and insect hot spots, asymptomatic virus-infected plants, harvest crews) are beyond the control of the researcher. Understanding field variability requires yield mapping, which is not currently done for vegetables.

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