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Analysis of within location non-replicated multi-locational on-farm yield trials for testing adaptability of crop varieties

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Abstract

Within location replication is necessary for efficient analysis of multi-locational on-farm yield trials for testing wide adaptability of crop varieties using presently available methods. However, within location replication is practically difficult, comparatively more expensive and cumbersome even with few varieties in the test. A method to efficiently analyze within location non-replicated multi-locational on-farm yield trials is proposed. In the proposed method, non-replicated trial is conducted in each location and yield deviations of varieties from the maximum yield in each location are computed and an analysis of variance is performed on variety yield deviations pooled over all locations. Mean deviation ($\bar{d}$) cand variance of deviations (s^2) across locations are computed for each variety. Varieties are selected simultaneously for significantly lower and lower s^2 and the variety with the lowest $\bar{d}$ and the lowest 2 is the most adaptable varietyin the test. The efficiency, effectiveness and the reliability of the proposed method is illustrated in comparison to the most appropriate presently available method with within location replication taking rice (*Oryza sativa* L.) as an example.

Key words: Adaptability, crop varieties, multi-locational on-farm yield trials, within location non-replication

Introduction

Crop varieties that are recommended for cultivation should possess wide adaptability over diverse farm environments. Several univariate methods are available to test wide adaptability of crop varieties. Univariate methods such as regression methods (Eberhart and Russell 1966) and variance component methods (Abeysiriwardena et al. 1991; Anputhas et al. 2011) that analyze genotype by environment (GE) interaction are efficient and effective only if the environment is quantified accurately by the average response of varieties in the test. As the maximum number of varieties included in on-farm yield trials rarely exceeds five, quantifying environment by the average response of varieties becomes aberrant so that none of these methods is useful in analyzing on-farm yield trials. The ranking method proposed by Das (1982) requires comparatively greater number of replications within location, which is difficult to achieve in on-farm trials and it does not provide any useful stability parameter.

The additive main effect and multiplicative interaction (AMMI) and GGE by-plot analyses are frequently used to study GE interaction in recent years (Gauch et al., 2008). AMMI analysis was designed to address the "which-won-where" patterns which are not usually easy for visualization. The bi-plot analysis displays yield trait relations in individual environment and addresses how GE interaction for yield can be explored by indirect selection for other traits (Yang 2005). Use of other traits as explanatory variables is subject to debate. The heritability adjusted-genotype main effect plus genotype-environment interaction (HA-GGE) (Yan and Holland 2010) was used by Luo (2015) mainly to evaluate test environments and for classification of regional ecological zones into mega-environments rather than to evaluate wide adaptability of sugarcane cultivars based on agronomic concept of adaptability. The method proposed by Abeysiriwardena (2001) as an improvement to the method of Lin and Binns (1988) is very efficient and effective in conducting and analyzing on-farm yield

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trials of crop varieties. However, all these methods require within location replication in yield trials. Nielson (2010) insisted to have replications within a farm in on-farm trials to estimate the residual or error variance.

Within location replication in multi-locational yield trials in farmers' fields even with few varieties is practically difficult, comparatively more expensive and cumbersome. In addition, it frequently encounters the problem of error heterogeneity among locations so that all the test locations may not be included in the final analysis. If a method to analyze data from within location non-replicated multi-locational yield trials is available, it would be very useful to make on-farm multi-locational variety testing program simple, easy and comparatively more practically feasible, less expensive and less cumbersome. The necessity of having within location replications for accurate estimation of variety yield can be avoided by having large plots. In rice, on-farm yield trials are conducted in 6m × 3m plots so that they are large enough to avoid aberrant plot yield data (Abeysiriwardena 2001). The objective of the present study is to propose an efficient method of analyzing within location non-replicated multi-locational on-farm yield trials for testing adaptability of crop varieties taking rice as an example. The proposed method will be compared with the method of Abeysiriwardena (2001) which is the most appropriate reference method.

Table 1. Analysis of variance for the variety deviation from the maximum response based on the proposed method

Source	df	SS	Ms
Total	$np - 1$	$\sum_{i=1}^{n}\sum_{i=1}^{p} d_{ij}^2 - \frac{(d..)^2}{np}$	
Variety (v)	$p - 1$	$\sum_{i=1}^{p} d_{i.}^2 - \frac{(d..)^2}{np}$	msv*
Location/v	$p(n - 1)$	$\sum_{j=1}^{n}\sum_{i=1}^{p} d_{ij}^2 - \sum_{i=1}^{p} d_{i}^2.$	msl(v)
V_1	$n - 1$	$\sum_{j=1}^{n} d_{1j}^2 - \frac{\left(\sum_{j=1}^{n} d_{1j}\right)^2}{n}$	msv_1
⋮	⋮	⋮	⋮
V_p	$n - 1$	$\sum_{j=1}^{n} d_{pj}^2 - \frac{\left(\sum_{j=1}^{n} d_{1j}\right)^2}{n}$	msv_p

* Indicates msv is tested against msl(v) as locations are random

Materials and methods

Proposed method is a modification of the method of Abeysiriwardena (2001) which was used as the reference method where variety superiority is measured by the distance of variety's response from the maximum response among all varieties tested in a given location. In the reference method trial in each location is replicated whereas in the proposed method trial in each location is non-replicated. The modified statistical model for the proposed method is given below and the ANOVA is presented in Table 1.

$$d_{ij} = \mu + V_i + L(V)_{ij}$$

Where, d_{ij} = grain yield deviation of the i^{th} variety in the j^{th} location from the maximum variety grain yield in that location, μ = grand mean of the plot yield deviations, V_i is the effect of the i^{th} variety, $L(V)_{ij}$ is the effect of the j^{th} location within i^{th} variety and i = 1….p and j = 1…n. In the proposed method, two adaptability parameters *viz*., mean deviation across locations $(\bar{d}_i)$ and the variance of deviations across locations or the stability parameter, s_i^2, for each variety are computed as same as in the reference method.

In the model of the proposed method, varieties are fixed and the locations are random so that V_i term is tested against the $L(V)_{ij}$ term as indicated by Eberhart and Russell (1966) and McIntosh (1983). Cochran and Cox (1957) also indicated that the ratio of genotype mean square to the genotype × environment interaction mean square provides test for the null hypothesis that there are no differences among the true genotype means provided that the genotypes be further partitioned into a set of components and that all these components be tested for their interaction with the environment. In addition, the expected variance of varietal deviations (varietal differences) across locations is the sum of the yield variances across locations of the two respective varieties (Dudewiez 1976), the yield variance of each of which separately having chi-square distribution (Snedcor and Cochran 1980).

If the V_i term is significant, mean separation is performed using Duncan's Multiple Range (DMR) test.

In addition, stability parameters are tested using Bartlett's test for homogeneity of variances (Bartlett 1947). If the stability parameters are found to be heterogeneous, separation of variances has to be done to detect what variances are lower or higher than the others. This can be achieved by performing F tests pair-wise with n – 1 degrees of freedomfor each variance (variety). Here the two tailed F test has to be performed and null hypothesis of equal variances is rejected if $F > F^{n-1}_{n-1,\propto/2}$ or $F < F^{n-1}_{n-1,\propto/2}$. Note that with n – 1 degrees of 'freedom for' both numerator and denominator, $F <^{n-1}_{n-1,1\propto/2} = (F^{n-1}_{n-1,\propto/2})^{-1}$. By this way, all the variety variances can be separated from each other and similarity groups of variances can be identified. When variances are separated, it is possible that one s_i^2 is zero and consequently the F statistic is either 0 or ∞. This would not be a problem according to the rejection criterion described above. A zero variance or zero mean will not be a problem for mean comparison either. Mean comparison can be performed in the usual way.

In the reference method, both V_i and $L(V)_{ij}$ termsare tested for significance against the pooled error as trials within environments are replicated. If V_i term is significant, computed mean deviations across environments for varieties (D_is) are separated using DMR test. If the V_i term is significant, variance of the variety deviations (υ_i^2) or the stability parameter for each variety is computed and tested against the pooled error by an F test to see whether it is significant or different from zero. Varieties are selected simultaneously for lower D_i and non-significant υ_i^2.

Selection criteria

The variety giving the highest grain yield in all locations would be the best or the most adaptable variety in the test. Such a variety would have zero mean and zero variance for the variety deviations. Thus, varieties are selected simultaneously for comparatively lower $\bar{d}_i$ and s_i^2.

Data

Grain yield data from five rice varieties of 3 ½ months maturity duration tested for their adaptability over 25 locations in farmers' fields in the Low Country Dry & Intermediate Zone (LCD&IZ) which is the major rice growing region in Sri Lanka were used in the study. The five varieties were AT 06-650, Ld 3-6-12, Bg 3R, Ld 356 and Bg 358. Out of the five, Ld 356 and Bg 358 were standard checks which are popularly grown in Sri Lanka. Other three were newly developed promising lines from three rice breeding stations.

All the varieties were planted in a Randomized Complete Block design (RCBD) with two blocks in each location. Reference method was applied by treating the data from two blocks over all locations as data from a replicated trial with two replications in each location. The proposed method was applied by treating the data from two blocks over all locations as two sets of data, one set representing block 1 data over all locations (Non-replicated Trial 1) and the other set representing block 2 data over all locations (Non-replicated Trial 2). This was possible due to the fact that block 1 and 2 in each location have been randomly assigned. As the trials were conducted in farmers' fields, large experimental plots of 6 × 3 m^2 size were used in all locations. The pests and diseases that may not uniformly affect different varieties were controlled in all locations. Grain yield data were recorded in the standard way and grain yield in each plot was adjusted to 14% moisture level.

Block 1 and block 2 data over locations were analyzed separately as data from two independent non-replicated trials with the proposed method, for the purpose of testing the precision of the proposed method on repeated tests. Variety deviations were computed as the deviation of variety grain yield from the maximum variety grain yield in each location for each independent non-replicated trial separately and the adaptability parameters of $\bar{d}_i$ and s_i^2 for each variety were computed and tested for significance according to the proposed method.

The proposed method was compared against the reference method. For the reference method, trial in each location was considered as in a RCBD with two blocks. Here, grain yield deviation of each variety in each replicate (each plot) from the maximum plot grain yield (maximum response among all plots) in each environment was computed. Average superiority (D_i) and the stability parameter (υ_i^2) across environments for each variety were computed and tested for significance.

Results and discussion

The grain yield of five rice varieties in Trial 1 and Trial 2 at 25 locations in the LCD&IZ of Sri Lanka are presented in Table 2. Note that Trial 1 and Trial 2 were considered as non-replicated trials. In the pooled analysis of variance of grain yield data considering trial in each location was a replicated trial with two blocks (Trial 1 and Trial 2 data were taken as block 1 and block 2 data), mean squares for location was found to be highly significant (P <0.01) indicating that the locations used in the study were different from each other. Location means varied from 3.78 t/ha the lowest to 9.62 t/ha the highest. This satisfied the prerequisite to have diverse locations in a variety adaptability evaluation test though the locations have been selected randomly.

Table 2. Grain of yield five rice varieties in the 3½ month maturity duration in Trial 1 and Trial 2 and location mean at each of 25 test locations in the Dry and Intermediate Zones of Sri Lanka (*tha*$^{-1}$)

Location	Variety										Location mean
	At 06-650		Ld 3-6-12		Bg3R		Ld356		Bg358		
	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2	
1	10.17	10.02	9.02	9.23	7.17	8.08	7.40	7.01	8.58	9.06	8.57
2	10.17	11.10	8.71	8.86	7.24	7.09	7.40	6.47	9.64	10.00	8.66
3	8.86	9.25	8.48	8.71	8.24	8.63	7.76	7.14	9.09	9.56	8.56
4	9.25	8.85	6.93	7.31	0.25	10.01	6.55	6.93	10.02	9.62	8.47
5	5.85	5.01	3.46	4.00	6.55	6.16	3.85	4.63	6.16	5.86	5.15
6	7.32	8.86	8.48	8.85	11.17	8.09	10.02	8.85	8.48	8.09	8.82
7	5.39	5.01	5.24	5.55	7.78	7.63	4.18	5.24	5.55	5.24	5.74
8	9.86	10.00	9.25	9.62	9.64	10.00	10.00	9.64	9.33	8:85	9.62
9	3.03	3.13	4.00	3.94	3.25	3.08	4.32	4.16	4.39	4.47	3.78
10	6.10	5.77	4.47	5.62	3.78	1.62	4.78	5.16	4.70	1.92	4.39
11	7.33	8.23	5.95	5.62	4.97	5.27	5.54	5.40	5.66	6.04	6.00
12	5.08	5.32	5.24	4.78	4.10	4.69	5.24	5.31	4.82	5.04	4.96
13	6.55	6.47	6.01	5.77	5.82	5.50	6.32	6.16	5.43	5.19	5.92
14	7.55	7.31	6.63	6.31	4.78	6.30	4.62	5.16	5.31	5.01	5.90
15	6.17	5.39	5.78	5.39	5.24	5.55	5.01	4.62	6.55	5.78	5.54
16	4.66	4.96	4.62	5.00	4.55	4.31	3.86	4.22	5.40	5.00	4.66
17	3.08	3.24	4.01	3.93	3.54	3.08	4.32	4.16	4.39	4.47	3.82
18	6.32	6.55	4.62	5.78	4.81	5.51	6.93	5.78	6.32	5.39	5.80
19	6.01	6.16	5.01	5.39	4.85	4.09	6.39	5.01	5.70	6.16	5.48
20	4.62	5.01	5.01	4.62	4.62	4.24	3.85	4.24	5.39	5.01	4.66
21	7.05	7.43	5.78	5.54	2.75	5.72	2.61	5.64	6.37	5.87	5.81
22	6.16	6.24	5.21	3.38	5.01	3.93	6.16	5.62	5.70	5.86	5.33
23	9.25	10.02	6.93	7.71	9.25	10.02	8.48	9.25	10.38	11.18	9.24
24	8.86	7.71	8.86	6.92	5.85	7.01	6.16	5.24	5.24	7.71	6.95
25	10.48	8.71	9.25	9.62	10.02	10.16	6.55	6.93	8.75	7.03	8.75
Variety mean	7.01	7.03	6.28	6.30	6.23	6.23	6.01	5.92	6.69	6.54	

Mean deviation $(\overline{d_i})$ and the stability parameter (s_i^2) of the proposed method under two within location

Table 3. Mean deviation ($\bar{d}$) and the stability parameter (s^2) under two within location non-replicated trials of the proposed method in comparison to the mean deviation (*D*) and the stability parameter (υ^2) of the reference method with within location replication for five rice varieties tested in 25 locations in the Dry and Intermediate Zones of Sri Lanka

Variety	Adaptability parameters[a]								
	Within location replicated method			Within location non-replicated or proposed method					
				Trial 1			Trial 2		
	D	v^2	AR[b].	$\bar{d}$	s^2	AR	$\bar{d}$	s^2	AR
At 06-650	0.74a	0.59**	1	0.60a	0.86a	1	0.43a	0.49a	1
Ld 3-6-12	1.47bc	0.87**	3	1.32bc	0.99a	3	1.17b	1.01b	3
Bg 3R	1.52bc	1.02**	3	1.37bc	1.00a	3	1.23b	1.34b	3
Ld 356	1.77c	1.50**	4	1.60c	1.70a	4	1.54b	1.49b	3
Bg 358	1.13ab	0.96**	2	0.91ab	0.99a	2	0.93ab	1.20b	2

[a]Values with the same letter within a column are not significantly different (*P* < 0.05); [b]Adaptability Rank - Lower the rank higher the adaptability; ** Indicates values are significantly higher than zero (*P*< 0.01).

non-replicated trials in comparison to the mean deviation (D_i) and stability parameter (υ_i^2) of the reference method with within location replication for each of five varieties tested in 25 locations in the LCD&IZ of Sri Lanka are presented in Table 3. In both Trials, when variety selection was performed simultaneously for comparatively lower $\bar{d}_i$ and lower s_i^2, variety At 06-650 showed the highest adaptability (rank 1) followed by the variety Bg 358 (rank 2). The varieties Ld 3-6-12 and Bg 3R were ranked 3 so that they were similar in their adaptability but inferior to that of Bg 358. However, gauging adaptability of Ld 356 was inconsistent over two Trials. In Trial 1, Ld 356 was found to be the least adaptable with rank 4 while in Trial 2 it was found to be similar in adaptability to Ld 3-6-12 and Bg 3R with rank 3. Thus, gauging adaptability of varieties was exactly the same when they were at comparatively higher adaptability range but slightly different when they were at relatively lower adaptability range.

Interestingly, both the reference and the proposed methods gauged adaptability of five rice varieties in farmers' fields exactly the same at comparatively higher adaptability range except for the minor differences found at the lowest adaptability level in Trial 2 with respect to Ld 356. In both methods, variety At 06-650 was found to be superior in its adaptability in farmers' fields to Bg 358 which is one of the most popular rice varieties in the LCD&IZ of Sri Lanka. Similarly, variety Ld 356 which is not popular in the LCD&IZ of Sri Lanka and Ld 3-6-12 and Bg 3R which were newly developed lines, were found to be inferior to Bg 358. In addition, Ld 3-6-12 and Bg 3R were found to be similar. Thus, the proposed method with within location non-replicated trials appeared promising and reliable and can effectively be used for testing adaptability of rice in farmers' fields.

Value of the proposed method

Proposed method is simple, straight forward and technically sound. Its practical feasibility is comparatively higher and it is less cumbersome, easy to implement and less expensive as it avoids within location replication in on-farm trials. It introduces a test for homogeneity of variances and variance ratio test for separation of variances if variances are found to be heterogeneous. This improves the efficiency of variety stability evaluation. In addition, the proposed method is free from the assumption of error homogeneity among locations.

The proposed method was able to produce almost consistent results over independent adaptability tests of rice conducted with the same set of varieties in the same locations. Also its evaluation of rice variety adaptability in farmers' fields was very similar to that of the reference method with within location replications.

Authors' contribution

Conceptualization of research (SA, SS); Designing of the experiments (SA, SS); Contribution of experimental materials (SA, SS); Execution of field/lab experiments and data collection (SA, SS); Analysis of data and interpretation (SA, SS); Preparation of the manuscript (SA, SS).

Declaration

The authors declare no conflict of interest.

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