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Efficiency of check-plot designs in unreplicated field trials

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Abstract Check-plot designs have a lower selection intensity than unreplicated non-check-plot designs if both the number of test lines to be selected (s) and of total plots in the trial (N) are kept constant. For a check-plot design to be more efficient, local control must effectively reduce the plot error variance and increase heritability to such a level that it compensates for the corresponding loss in selection intensity and makes the expected gain from selection at least equal to that in the non-check-plot design. To realize this goal, the required minimum reduction in plot error variance in a check-plot design (relative to that in a non-check-plot design) depends on (1) check-plot frequency f_c, (2) fraction $k = s/N$, and (3) ratio $w_0 = \sigma_0^2/\sigma_g^2$ of non-check-plot design plot error variance σ_0^2 to genetic variance σ_g^2 among test lines. Lower w_0 and higher f_c and k are found to require a relatively higher reduction in plot error variance in check-plot designs. A condition is derived to show when a check-plot design may never be more efficient.

Key words Check-plot designs · Efficiency · Expected gain from selection · Local control · Unreplicated field trials

Introduction

Due to limitations in the availability of genetic material, particularly in the early stages of a breeding program, breeders generally have little option but to undertake unreplicated field trials of test lines. In such cases, the effective local control of environmental factors, which generally act in a non-uniform manner over the trial field, assumes particular importance with respect to increasing the expected gain from selection. In the hope of realizing this goal, breeders often use check-plot (CP) designs, these include systematic CP designs (Baker and McKenzie 1967), augmented designs (Federer 1961; Federer and Raghavarao 1975; Federer et al. 1975), and modified augmented designs (Lin and Poushinsky 1983, 1985). Local control in a CP design takes the form of check-plot observations, which are used to adjust the phenotypic values of test lines for the effect of environmental factors.

A characteristic feature of any CP design is that a certain fraction of the total plots in the trial is assigned to the check varieties, with the remaining plots being allocated to unreplicated test lines. Relative to a situation where all plots in the trial occupy unreplicated test lines, an immediate consequence of using a CP design is a reduction in the selection intensity if the number of test lines to be selected and total number of plots in the trial remain the same. Under these circumstances, a CP design may deliver a lower expected gain unless local control effectively reduces the plot error variance and increases heritability to a level where it compensates for the corresponding loss in selection intensity. How effective local control has to be in a CP design is the objective of this paper. This question was examined by Kempton (1984), but his calculations seem to be incorrectly derived.

Theory

Consider a CP design in which C plots are assigned to check varieties and T_c plots to T_c unreplicated test lines, with

$$N = C + T_c,$$

being the total number of plots in the trial. The frequency of check plots, f_c, and that of plots assigned to test lines, f_t, in the design are

$$f_c = \frac{C}{N}, \quad f_t = \frac{T_c}{N}$$

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with

$f_c + f_t = 1.$

Let

$s = kN$

be the number of test lines to be selected, expressed as the k-th fraction of N, with $0 < k < 1$ and $0 < s < T_c$. The fraction of test lines selected, α_c, becomes

$$\alpha_c = \frac{k}{1 - f_c},$$

which is independent of N. Let the genetic gain (G_c) expected from the use of the CP design, after the adjustment of phenotypic values of test lines, be

$$G_c = i_c h_c \sigma_g, \tag{1}$$

where

$$i_c = \frac{z_{\alpha_c}}{\alpha_c}$$

is the selection intensity;

$$h_c^2 = \frac{\sigma_g^2}{\sigma_g^2 + \sigma_c^2} = \frac{1}{1 + w_c}, \quad w_c = \frac{\sigma_c^2}{\sigma_g^2}, \tag{2}$$

is the coefficient of heritability; σ_g^2 is the genetic variance among test lines; σ_c^2 is the plot error variance after adjustment based on check-plot observations; and z_{α_c} is the density of the standrd normal distribution at the point of truncation corresponding to α_c.

Now consider a non-check-plot design where $C = 0$ and all of the $N = T_0$ plots in the trial occupy T_0 unreplicated test lines with the consequence $f_c = 0$; hence,

$$\alpha_0 = k, \text{ and } i_0 = \frac{z_k}{k}.$$

Leting σ_0^2 be the plot error variance, either when no adjustment is done or the adjustment is affected using a strategy such as moving means, the expected gain (G_0) may be expressed as

$$G_0 = i_0 h_0 \sigma_g, \tag{3}$$

where

$$h_0^2 = \frac{\sigma_g^2}{\sigma_g^2 + \sigma_0^2} = \frac{1}{1 + w_0}, \quad w_0 \frac{\sigma_0^2}{\sigma_g^2}. \tag{4}$$

Since $T_c < T_0$, we shall have

$\alpha_c > \alpha_0$, and $i_c < i_0$.

If the CP design is more efficient, it must have σ_c^2 at a level that it compensates for the loss incurred through a reduced i_c so that G_c is at least the same as G_0; i.e., $G_c \geq G_0$. From Eqs. 1 and 3 this implies that

$i_c h_c \geq i_0 h_0$,

or

$$\frac{h_0^2}{h_c^2} \leq \left[\frac{i_c}{i_0}\right]^2,$$

which, using Eqs. 2 and 4, simplifies to

$$\frac{w_c}{w_0} = \frac{\sigma_c^2}{\sigma_0^2} \leq \left[\frac{i_c}{i_0}\right]^2 \left[1 + \frac{1}{w_0}\right] - \left[\frac{1}{w_0}\right]. \tag{5}$$

For a given f_c, k, and w_0, the condition 5 can be computed to determine what reduction in σ_c^2, relative to σ_0^2, will be required to ensure $G_c \geq G_0$.

Illustration and discussion

To illustrate inequality 5, Tables 1 and 2 present values of (σ_c^2/σ_0^2) for $k = 0.05$ and 0.10, respectively, at some selected values of f_c and w_0. These values of (σ_c^2/σ_0^2) correspond to $G_c = G_0$. For $G_c > G_0$, the values of (σ_c^2/σ_0^2) should be less than those reported in Tables 1 and 2. The following general observations may be made on the basis of these results.

At certain f_c's, particularly large values, it is not possible to ensure $G_c = G_0$. This occurs because for some values of f_c's, (σ_c^2/σ_0^2) is negative. For example, in Table 1 ($k = 0.05$) at $f_c = 0.40$ corresponding to $w_0 = 0.20$, we have $(\sigma_c^2/\sigma_0^2) = -0.227$. To have $G_c \geq G_0$, (σ_c^2/σ_0^2) should be a positive quantity which, from Eq. 5 implies

$$w_0 > \left[\frac{i_0}{i_c}\right]^2 - 1. \tag{6}$$

Thus, whenever the righthand side in Eq. 6 is more than the given w_0 value, we cannot have $G_c = G_0$; in which case a CP design is certainly not an efficient design choice.

Table 1 Minimum values of σ_c^2/σ_0^2 to maintain $G_c = G_0$ at $k = 0.05$

f_c:	0.60	0.50	0.40	0.33	0.25	0.20	0.10	0.05	0.00
α_c:	0.125	0.100	0.083	0.075	0.067	0.062	0.056	0.053	0.050
i_c:	1.647	1.755	1.840	1.887	1.940	1.968	2.018	2.042	2.063
I:	0.569	0.382	0.257	0.195	0.131	0.099	0.045	0.021	0.000
w_0	σ_c^2/σ_0^2								
0.20	−1.176	−0.658	−0.227	0.020	0.306	0.460	0.741	0.878	1.000
0.50	−0.088	0.171	0.386	0.510	0.653	0.730	0.870	0.939	1.000
1.00	0.275	0.447	0.591	0.673	0.769	0.820	0.914	0.959	1.000
2.00	0.456	0.585	0.693	0.755	0.826	0.865	0.935	0.969	1.000
5.00	0.564	0.668	0.755	0.804	0.861	0.892	0.948	0.976	1.000

Table 2 Minimum values of σ_c^2/σ_0^2 to maintain $G_c = G_0$ at $k = 0.10$

f_c :	0.60	0.50	0.40	0.33	0.25	0.20	0.10	0.05	0.00
α_c :	0.250	0.200	0.167	0.150	0.133	0.125	0.111	0.105	0.100
i_c :	1.271	1.400	1.500	1.554	1.615	1.647	1.704	1.731	1.755
I :	0.907	0.571	0.369	0.275	0.181	0.136	0.061	0.028	0.000
w_0	σ_c^2/σ_0^2								
0.20	−1.853	−1.182	−0.617	−0.295	0.081	0.284	0.656	0.837	1.000
0.50	−0.426	−0.091	0.191	0.352	0.540	0.642	0.828	0.918	1.000
1.00	0.049	0.273	0.461	0.568	0.694	0.761	0.885	0.946	1.000
2.00	0.287	0.455	0.596	0.676	0.770	0.821	0.914	0.959	1.000
5.00	0.429	0.564	0.677	0.741	0.816	0.857	0.931	0.967	1.000

For those f_c's for which Eq. 6 holds but the size of the difference $(w_0 - I)$ is small where

$$I = \left[\frac{i_0}{i_c}\right]^2 - 1,$$

local control in the CP design will have to be highly effective even to maintain $G_c = G_0$. This is because the smaller the difference $(w_0 - I)$, the less is the value of (σ_c^2/σ_0^2). In such cases, special care will have to be exercised in selecting an appropriate CP design.

The fraction k at higher values and the ratio w_0 at lower values will necessitate a more stringent local control in a CP design.

Provided w_0 could be specified, based on, say, experience with the crop and trial site, the ideas presented here could be useful for determining whether a CP design could be more efficient for number of test lines included relative to the number of checks included.

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