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DESIGN EFFECTS OF COMPLEX SAMPLING STRATEGY ON ANOVA MIXED EFFECTS MODEL -- AN EMPIRICAL STUDY

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Abstract: The researchers in subject matter areas (e.g., social and health sciences, agriculture etc.) have long been using analysis of variance techniques to analyze sample survey data, assuming that data are obtained through simple random sampling without replacement (SRSWOR) scheme. But most of the commonly used survey designs employ complex sampling designs involving multistage sampling schemes, because of operational and cost considerations. This paper, therefore, investigates empirically the effects of Complex Sampling Strategy (CSS) vis-à-vis Simple Sampling Strategy (SSS) on ANOVA mixed effects model, through the analysis of data pertaining to experiments on cultivators' fields.

1. Introduction

It seems that technique of analysis of variance was developed by R.A. Fisher (1926) sometime between 1923-25 in connection with the field experiments in agriculture. Though subsequently, this technique was used extensively in design of experiments; it was only in 1947 that Eisenhart brought forth the assumptions underlying the analysis of variance under two postulates: Model I and Model II. Both the models are additive models with the difference that in Model I only the error-component is the random variable where as in Model II in addition to the error-component some or all the other effects in the experiment are also random variables. In the Analysis of variance, the main assumption is regarding the experimental errors. The experimental errors are assumed to be normally and independently distributed with the same variance (homoscedasticity). There are a number of papers which have direct or indirect consequence of examining the effect of departure from normality on the various tests carried out in the analysis of variance table. Amongst these, three papers by Hey (1938), Bartlett (1947) and Cochran (1947) [cf. Scheffee (1959), Tikkiwal, B.D. (1961)] are of interest. Also the researchers in subject matter areas (e.g., social and health sciences, agriculture etc.) have long been using analysis of variance techniques to analyze sample survey data, assuming that data are obtained through simple random sampling without replacement (SRSWOR) scheme. But most of the commonly used survey designs employ complex sampling designs involving multistage sampling schemes, because of operational and cost considerations.

In this article we propose to investigate the effect of complex sampling Strategy vis-à-vis Simple Sampling Strategy, involving SRSWOR, on ANOVA mixed effects model. We came across this problem while investigating the effect of using complex

Keyword. Design effects, ANOVA, Sampling Strategy, SRSWOR, SPPSWOR, Experiments on cultivators' fields.

sampling designs rather than using SRSWOR, as the situation so demands, for laying down an experiment on cultivators' fields.

In Sections 2 and 3 of the paper, we first present the details of Experiments on cultivators' fields and the data used in the present study. Section 4 discusses the simulation procedure to estimate yield under the mixed effects model and Section 5 gives the main results.

2. Experiments on Cultivators' Fields

2.1. Introduction. The agricultural productivity is influenced by several factors such as climate, soil, crop, fertilizers applied, seed varieties, irrigation and management practices followed. Higher productivity by judicious use of inputs and improved management practices can be achieved by conducting experiments on agricultural research stations and also on cultivators' fields and then comparing their findings for appropriate recommendations to the cultivators.

Through a large number of agricultural experiments on important crop like paddy, maize, wheat, gram, barley etc. spread over different years since 1948; it has been observed that the response to fertilizers on cultivators' fields are different from those on Government Agricultural Research Stations. The doses which are adequate on research stations are generally too high on cultivators' fields. According to this study, areas which showed no response to phosphate or potash on agricultural research stations showed good response on the cultivators' fields.

The method for laying down the experiments on cultivators' fields for testing the research findings, pertaining to fertilizers application under actual farming conditions was given by Panse and Sukhatme (1953). The experiments on cultivators' fields in India have been conducted as part of All India Coordinated Agronomic Research Project, a project in existence since 1956-57. The technical programme has been revised and enlarged from time to time in the light of the experience gained in previous years and also in view of changing agricultural needs. The methodology now used in the technical programme as discussed in the following section is more or less stabilized [cf. Soni & Bhargava (1948)].

2.2. Methodology. The experiments on cultivators' field are being conducted under dry land, assumed rainfall and irrigated conditions. For the purpose of conducting experiments, a certain number of districts[1] spread over different states of India are selected purposely. Each district selected from a particular state is then stratified into four agricultural homogeneous zones by suitable combination of contagious tehsils/ talukas, taking into consideration homogeneity in respect of climate, soil, cropping pattern, rainfall and availability of irrigation water etc., to the extent possible. Each zone is further divided into a number of clusters, depending on tehsil/talukas or revenue circle taking into considerations soil, climate and cropping aspects. Out of the clusters, so formed, two clusters are selected with SRSWOR in each zone. Each selected cluster is further divided into three blocks. A block in a cluster is formed

[1] In Indian administrative set-up, the country consists a number of States, each State consists of a number of Districts, each Districts consists a number of Tehsil, and each Tehsils consists of Villages, households etc.

by suitable grouping the units like revenue circle, patwari circle, VLW circle, thana or any other convenient administrative unit. One block is further selected from each of the two clusters, again by SRSWOR scheme. Thus, we get two blocks in a zone for experimentation. **In state like Rajasthan, still there is no clustering and blocks are directly selected from the respective zones.**

In each selected block, a certain number of villages are selected again by the SRSWOR scheme. In each selected village, three cultivators are randomly selected again by same sampling scheme. In each of the cultivators' fields, plots of recommended size are laid out for experimentation. The recommended size of the plot is generally 50 sq. meters for simple fertilizer trials, whereas it can be up to 200 sq. meters for other type of experiments.

However, they are still of larger sizes than of those used in crop estimation surveys. Three different types of experiments are conducted in the three fields of a village. The Randomized Block Design is generally being used in these experiments. However, for certain complex experiments, split – plot design is being used. A comprehensive review of the experiments is provided by Soni & Bhargava (1984).

2.3. Mixed Effects Model for Analysis of Data. The analysis of these experiments in India is currently done through fixed effects model approach. However, as clusters, blocks within clusters and then villages within blocks are selected randomly, it is more logical to use mixed effects model approach otherwise it may give an erroneous results as pointed out by Khidhair (1988) and Jain (1994). We shall, therefore, examine the impact on findings from such experiments, using mixed effects model approach. For this we limit ourselves to the analysis of such experiments at zonal level and for the experiments in which we select unequal or equal number of villages in the selected blocks within zones as the case may be. Let us assume the following mixed effects model, for the analysis of data, ignoring the sampling design used. This approach for analysis of data is termed, in recent terminology, as M-approach as against two other approaches known as D and D-M approaches (Sarndal, 1981, Tikkiwal, 1960, 81).

Let $y_{ik\ell}$ denote, for ℓ^{th} treatment, the yield of a plot in a cultivator's field selected k^{th} village of i^{th} selected block in for $\ell = 1, 2, ..., \text{T}$; $k = 1, 2, ..., \text{V}$; and $i = 1, 2, ..., b$.

Let
$$y_{ik\ell} = \mu + \beta_i + \text{T}_\ell + (\beta\text{T})_{i\ell} + v_{ik} + \varepsilon_{ik\ell} \tag{1}$$
where,

$\mu = a$ constant quantity;

$\beta_i =$ The random effect of i^{th} block with

$\beta_i \sim$ N.I.D.$(0, \sigma_b^2)$, i.e., normally and independently distributed with mean zero and variance σ_b^2; $\text{T}_\ell =$ The fixed effect of ℓ^{th} treatment in the experiment with

$$\sum_{\ell=1}^{\text{T}} \text{T}_\ell = 0; \ (\beta\text{T})_{i\ell} \sim \text{NID}(0, \sigma_{bt}^2)$$

$\nu_{ik} =$ The random effect of k^{th} village in i^{th} block with $\nu_{ik} \mid i \sim \text{NID}(0, \sigma_\nu^2)$.

$\varepsilon_{ik\ell} =$ The random effect due to error with $\varepsilon_{ik\ell} \mid i, k \sim \text{NID}(0, \sigma_\epsilon^2)$.

It is further assumed that the random effects β_i, $(\beta T)_{i\ell}$, ν_{ik} and $\varepsilon_{ik\ell}$ are also mutually independent. Now the expected values of various sums of squares under the model given in Eq. (1) are presented in the following ANOVA table.

Table 1. ANOVA Table for Mixed – Effects Model

Source of Variation	*Sum of Squares (S.S.)*	*Degrees of Freedom (D.F.)*	*Expected Values of Mean Sum of Squares (M.S.S.)*
(i) Blocks	$VT\sum_i (y_{i..} - y...)^2$	$(b-1)$	$\sigma_\varepsilon^2 + V\sigma_{bt}^2 + T\sigma_v^2 + VT\sigma_b^2 = E(MSB)$
(ii) Treatments	$bV\sum_\ell (y_{..\ell} - y_{...})^2$	$(T-1)$	$\sigma_\varepsilon^2 + V\sigma_{bt}^2 + bV\sum_\ell T_\ell^2/T-1 = E(MST)$
(iii) Blocks x Treatments	$V\sum_{i,\ell} (y_{i.\ell} - y_{i..\ell.} - y_{..\ell} + y...)^2$	$(b-1)$ $(T-1)$	$\sigma_\epsilon^2 + V\sigma_{bt}^2 = E(MS(BXT))$
(iv) Villages in different blocks	$T\sum_{i,k} (y_{ik} - y_{i..})^2$	$b(V-1)$	$\sigma_\varepsilon^2 + T\sigma_v^2 = E(MSV)$
(v) Error	$\sum_{i,k,\ell} (y_{ik\ell} - y_{i.\ell} - y_{ik.} + y_{i..})^2$	$b(V-1)$ $(T-1)$	$\sigma_\varepsilon^2 = E(MSE)$
Total	$\sum_{i,k,\ell} (y_{ik\ell} - y...)^2$	$bVT-1$	

It may be noted here that Scheffe (1956, 1959) suggested a mixed effects model slightly different from one given in (1), which assumes

$$\sum_\ell (\beta T)_{i\ell} = 0 \tag{2}$$

Everything else in the ANOVA table remains the same. But Scheffe's model introduces unnecessary distribution problems and thereby unnecessary approximation in test procedures, which are avoided in the model presented in this section.

3. Details of Experimental Data

For the purpose of conducting experiments on cultivators' fields, a certain number of districts spread over different states of India are selected purposely. In state of Rajasthan, three districts are selected purposely for such experiments for consecutive three normal years and then they are replaced by other districts. For the year 1978-79 to 1980-81, the three selected districts in the state of Rajasthan were: (1) Chittaurgarh, (2) Bundi, and (3) Sawai Madhopur. Since 1980-81 was not considered a normal year due to drought situation in that year, the experiments were repeated in 1981-82 in the same blocks of these three districts which were selected for experimentation in 1980-81. Each of the districts was divided into four agriculturally homogeneous zones. We confine to data of Zone-1 for the present study. The Zone-1 of Chittaurgarh district consists of seven agricultural blocks (B-1 to B-7): Bijapur (B-1), Chhoti Sadri (B-2), Chittaurgarh (B-3), Ghosunda (B-4), Karjoo (B-5), Mangol (B-6), Nimbahera (B-7).

From these seven blocks the following two blocks B-2 & B-4 are selected by SRSWOR. Again from Block B-2 the following five villages are selected by SRSWOR: Dhamaniya (V-1), Semarthali (V-2), Narani (V-3), Barwara Gujar (V-4), and Chokri (V-5) and from block B-4 the following five villages are randomly selected: Ghousunda (V-6), Kashmor (V-7), Rooppura (V-8), Sajjan Pura (V-9), and Panchli (V-10). In each of these ten villages (of Zone-1) a cultivator's field is selected and experiment is laid out for the following twelve treatments T_1 to T_{12} (fertilizer trials).

The experimental data of the treatment-wise plot yield in different villages of B-2 and B-4.

T_1	$N_0P_0K_0$	T_2	$N_{40}P_0K_0$	T_3	$N_{80}P_0K_0$
T_4	$N_{120}P_0K_0$	T_5	$N_{40}P_{20}K_0$	T_6	$N_{80}P_{40}K_0$
T_7	$N_{120}P_{60}K_0$	T_8	$N_{40}P_{20}K_{20}$	T_9	$N_{80}P_{40}K_{40}$
T_{10}	$N_{120}P_{60}K_{60}$	T_{11}	$N_{120}P_{60}K_{40}$	T_{12}	$N_{120}P_{60}K_{20}$

+Zinc (or lime in acid soils)

Where, N denotes Nitrogen, P denotes Phosphorus, K denotes Postassium.

The analysis of data of Zone-1, further gives the following ANOVA Table 2.

Table 2. Analysis of Variance Table for experiments on cultivators' fields in Zone–1 of Chittaurgarh District in Rajasthan for wheat crop in Rabi Season 1979-80.

Source of Variation	*Sum of squares*	*Degree of freedom*	*Mean sum of squares*	*Variance Ratio F*
Block	5289.420	1	5289.420	
Treatments	7040.110	11	640.010	
Blocks × Treatments	539.980	11	49.089	
Villages in different blocks	1599.720	8	199.965	13.037
Error	609.350	88	6.924	
Total	15078.580	119	126.711	

4. Optimal Sampling Strategy and Simulation of Block-wise Yield

4.1. Optimal Sampling Strategy. As we have seen in Section 3 that for laying down experiments on cultivators' fields currently SRSWOR scheme is being used at the various stages of Sampling. In view of the fact that blocks are of unequal sizes, it may be better to use varying probability sampling scheme. Khidhair (1988) and Jain (1994) compared a number of sampling strategies with the one currently in use involving SRSWOR scheme through simulation studies. They conclude that Sampling strategy involving probability proportional to size without replacement scheme (SPPSWOR) along with Horvitz-Thompson estimator (1952) is the best strategy.

While shifting to a new sampling strategy, one should ensure that the design-effect of the new sampling strategy on the usage of analysis of variance technique for analysis of such experiments should not be very different from the design-effect of the current sampling strategy. Therefore, we now examine this aspect. For this purpose, we refer to the present sampling strategy as the simple sampling strategy (SSS). The alternative sampling strategy would consist of selection of blocks at the first-stage of sampling with SPPSWOR and then at the subsequent stages of sampling, units would be selected with SRSWOR. We shall refer this strategy as the complex sampling strategy (CSS).

For examination of relative design effect of CSS and SSS, on analysis of data under ANOVA mixed-effects model we first need to simulate the wheat-yield for each of the twelve treatments at block level and then the wheat yield of different villages and cultivators' fields in those villages falling in different blocks of the zone.

4.2. Simulation Procedure for Block Level Yield. For each of the twelve treatments it may be required to simulate the production of wheat at block level and the wheat-yields of different villages and cultivators' fields in those villages, falling in different blocks of Zone – 1 for the year 1979-80. We can do this simulation through appropriate analysis of sample data on treatment wise plot yield of cultivators' fields of five selected villages each from Sadri and Ghosunda Blocks (B-2 & B-4) ,described in Section 3; through ANOVA mixed – effects model given in Eq. (1)

Let $E(y_{ik\ell} \mid i)$ denote the true wheat-yield per hectare of i th block for ℓth treatment. Then the fact that production at block level being proportional to its area, except random component, gives $A_i E(y_{ik\ell} \mid i)$

Where, A_i denotes the area of the ith block and under the mixed-effects model given in Eq. (1). The Eq. (1) further gives

$$E(y_{ik\ell} \mid i) = \mu + \beta_i + T_\ell + (\beta T)_{i\ell} \text{ as}$$

$$y_{\ldots\ell} = \mu + \beta_{.} + \nu_{..} + T_\ell + (\beta T)_{.\ell} + \varepsilon_{.\ell}$$

where, the $E(y_{.\ell}) = \mu + T_\ell$

Therefore, we can use the following expression for the simulated production of ith block in Zone-1:

$$A_i\{y_{..\ell} + \beta_i + (\beta T)_{i\ell}\} \qquad (3)$$

for i representing those blocks not in the sample. For blocks in the sample, we note that

$$E(\bar{y}_{i.\ell} \mid i) = \mu + \beta_i + T_\ell + (\beta T)_{i\ell}$$

and therefore the simulated production for such sample blocks is given by $A_i \bar{y}_{i.\ell}$

The variance components σ_b^2 and σ_{bt}^2 are estimated unbiasedly for simulation purpose as follows, using results of E(MSS) given in Table 1.

$$\left.\begin{aligned} \hat{\sigma}_b^2 &= \frac{1}{VT}[MSB - MS(BXT) - MSV + MSE] \\ &\text{and} \\ \hat{\sigma}_{bt}^2 &= \frac{1}{VT}[MS(BXT) - MSE] \end{aligned}\right\} \qquad (4)$$

Table 2, gives for the present experiment $\hat{\sigma}_b^2 = 84.1215$ and $\hat{\sigma}_{bt}^2 = 8.4330$

5. Design Effects of CSS

Having obtained the simulated block-wise production, we now need to simulate the experiment under complex sampling strategy as well as under simple sampling strategy in order to study the design effect.

5.1. Simulation of Experiments under CSS and SSS. For simulation of an experiment to begin with, we first select two blocks and then five villages within blocks as per the specified sampling strategy. For simulation of the next experiment, we replace the selected block, with the selected villages there-in in the population and then again select two blocks and five villages within blocks as per the specified sampling strategy. Thus, we get two sets of blocks and villages which are statistically independent. We continue this process till we get 5,000 sets of blocks and villages, which are statistically independent.

In simulating each experiment, we come across following three types of cases:

Case 1. No block and therefore no village therein coincides with the two sampled blocks i.e. with B_2 and B_4 (as mentioned in Sec. 3).

Case 2. At least one block coincides with one of the two sampled blocks, but no village there-in coincides with the already selected five villages in the sampled block.

Case 3. At least one block coincides with one of the two sampled blocks and at least one village selected there-in coincides with one of the five villages of the sampled block.

We now give below simulation procedure to simulate 120 $y_{ik\ell}$ observations of an experiment, corresponding to a particular case using the mixed-effects model given in Eq. (1). We have

$$y_{ik\ell} = \mu + \beta_i + T_\ell + (\beta T)_{i\ell} + \nu_{ik} + \varepsilon_{ik\ell}$$

for $i = 1, 2$; $k = 1, 2, ..., 5$ and $\ell = 1, 2, ..., 12$.

For any value of $i = 1, 2, ..., 5$; we get the value of $\mu + \beta_i + T_\ell + (\beta T)_{i\ell}$ for $\ell = 1, ..., 12$ by the method given in Sub-section 4.2.

For a set belonging to group (i) or (ii), we draw five random observations from the population $v_{ik} | i \sim N(0, \sigma_v^2)$ for $i = 1, 2$. For each such random observation, we then draw twelve random observations from the population: $\varepsilon_{ik} | i, k \sim N(0, \sigma_\varepsilon^2)$. This will then complete the simulation of the experiment with 120 $y_{ik\ell}$ − observations corresponding to the set.

For a set belonging to group (iii), if only one block coincides with one of the two selected blocks for the conducted experiment, then for the other block, we follow the procedure as above to get 60 $y_{ik\ell}$ − observations where i now stands for the other block.

For a village, in the common block, which coincides with one of the five villages of the common block in the conducted experiment, we note that

$$E(y_{ik} | i, k) = \mu + \beta_i + T_\ell + (\beta T)_{i\ell} + \nu_{ik} \quad (5)$$

For such a village in the set, we draw twelve random observations from the population: $\varepsilon_{ik\ell} | i \sim N(0, \sigma_\varepsilon^2)$. Each of the twelve random observations when added to $y_{ik\cdot}$ will then give 12 $y_{ik\ell}$ − observations for i, k denoting the common block and the common village in that block. For a village not common to any of the five villages, we draw a random observation from the population: $v_{ik} | i \sim N(0, \sigma_v^2)$ and then 12 random observations from the population: $\varepsilon_{ik\ell} | i, k \sim N(0, \sigma_\varepsilon^2)$. In this manner we simulate all the 60 $y_{ik\ell}$ − observations for such a common block. We adopt Polar Method for simulation as discussed by Hsieh and Manski (1987, Sec.2, p. 542).

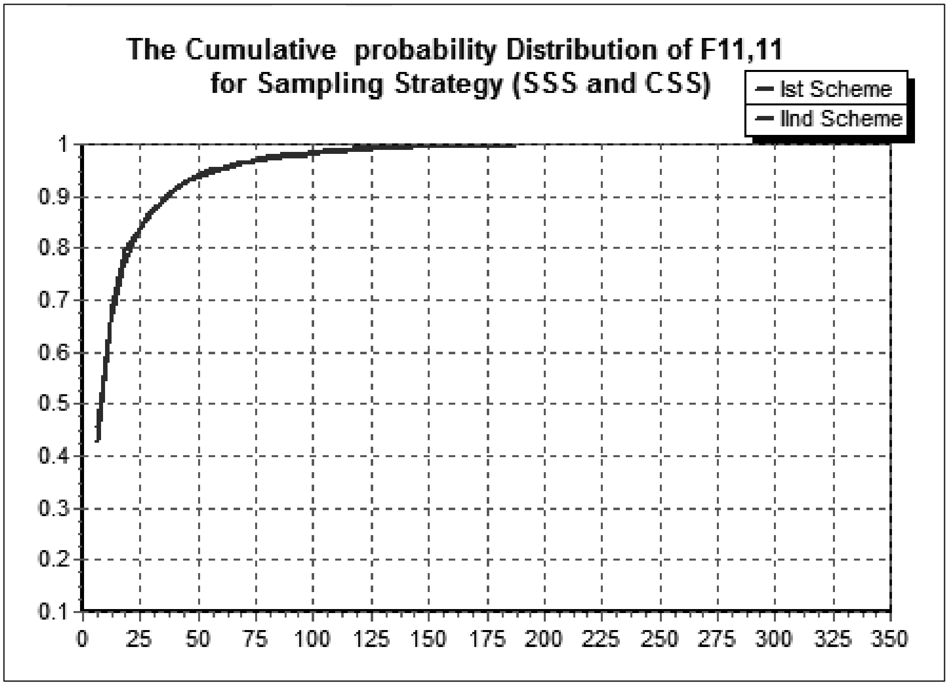
5.2. The F-values from Simulated Experiments. Following the procedure as described in Sec. 5.1, 5,000 experiments were simulated for each of the two sampling strategies SSS and CSS. They were then analyzed to obtain the following F-values:

$$F_{11,\,11} = \frac{\text{M.S.S. due to Treatments}}{\text{M.S.S. due to Blocks} \times \text{Treatments}} \tag{6}$$

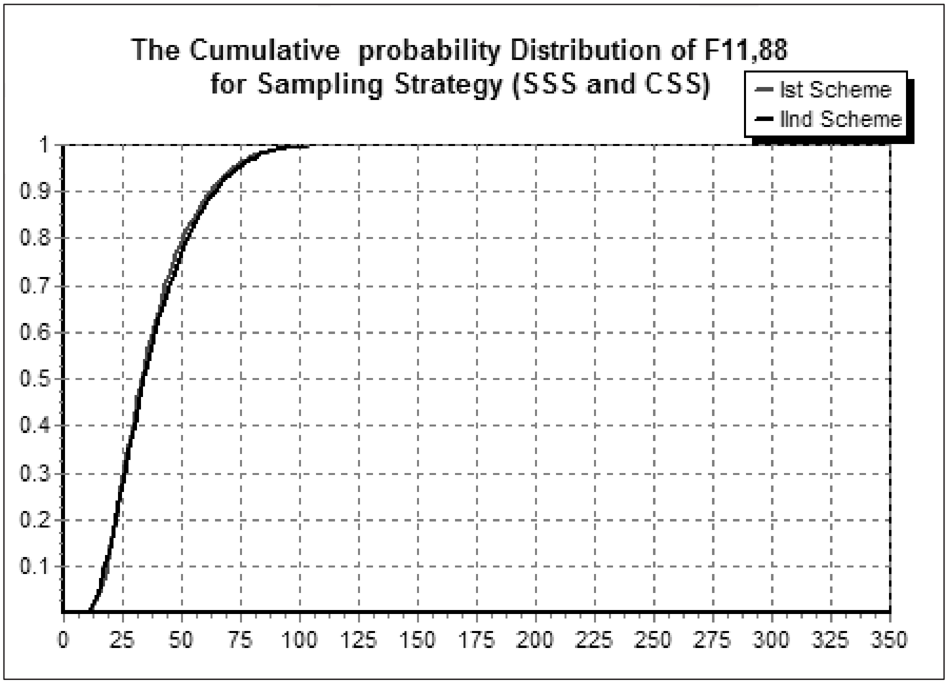
and

$$F_{11,\,18} = \frac{\text{M.S.S. due to Treatments}}{\text{M.S.S. due to error}} \tag{7}$$

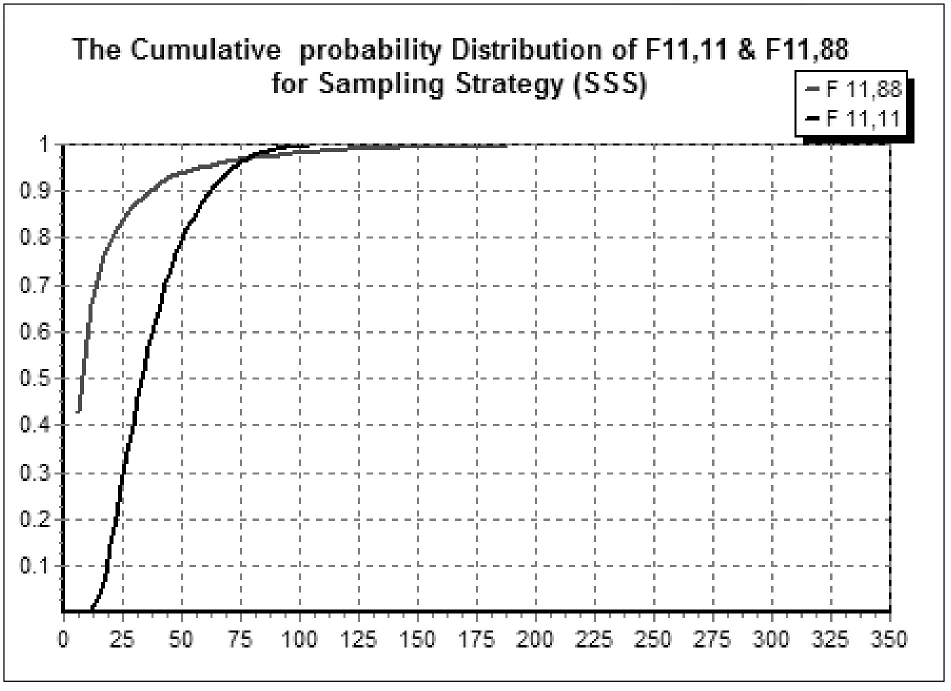
Since the treatment − effects are not zero in the simulation procedure, these F-values are the values from the respective non-null distributions $F_{11,11}$ and $F_{11,88}$. For various interpretations from these values, we need to plot the various cumulative probability F-distributions. For this, we calculate first the cumulative frequencies and cumulative probabilities of F-values that give the four different Graphs 1 to 4.



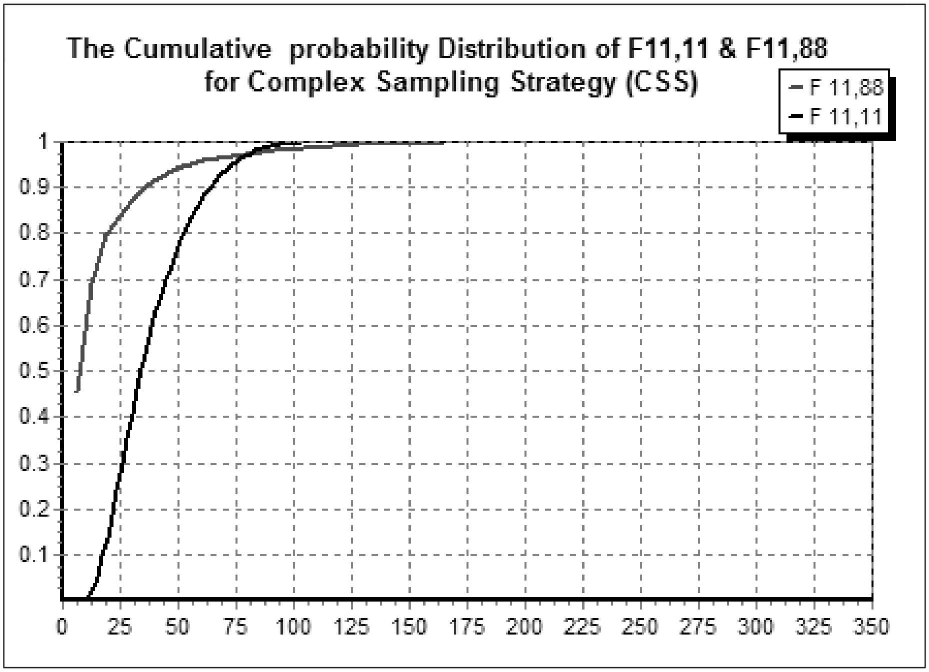
Graph 1



Graph 2



Graph 3



Graph 4

Conclusion 1. From the Graphs 1 and 2, we note that the cumulative probability distributions of $F_{11,11}$ and $F_{11,88}$ are nearly the same for all practical purposes for the two sampling strategies; showing thereby that the design-effect of the two sampling strategies is nearly the same.

From the Graphs 3 and 4, we note that the cumulative probability distributions of $F_{11,11}$ and $F_{11,88}$ differ from each other in both the sampling strategies. This then disturbs the second kind of error as well as the power of the test in using test procedure based on $F_{11,11}$ and $F_{11,88}$ rather than one based on $F_{11,11}$ alone or a combination of $F_{11,11}$ and $F_{11,88}$. In order to know to what extent these disturbances occur in the second kind of error as well as the power of the test, we proceed as follows.

We further calculate the probabilities of rejection of the null hypothesis that all treatment effects are equal, given that the alternative is ture. The rejection regions for this we take the usual 5 percent and 1 percent levels of significance in the F-distribution under normality assumption of yield data. We then find number of F-values, in each of the four sets of 5,000 such values for $F_{11,11}$ and $F_{11,88}$ under SSS and CSS respectively which are greater than these respective values. These numbers when divided by 5,000 give the powers of the test under different rejection regions. We also find the rejection regions when the second kind of error is fixed at 5 percent level of significance. This we do by arranging first 250 observations in ascending order in each of the four sets of 5,000 F-values.

The following tables give the powers of the tests as well as the rejection regions determined as above.

Table 3. The Powers of the Test under Different Rejection Regions

Level of Significance	*Critical Value of F*	*No. of F-Values greater then the critical value in SSS*	*Power of Test*	*No. of Values greater than the critical value in CSS*	*Power of the Test*
0.05 for $F_{11,11}$	2.82	3404	0.68	3366	0.67
0.01 for $F_{11,11}$	4.47	3125	0.63	3109	0.62
0.05 for $F_{11,88}$	1.92	5000	1.00	5000	1.00
0.01 for $F_{11,88}$	2.49	5000	1.00	5000	1.00

Table 4. Rejection Region for Second kind of Error at 0.05 Level of Significance for the Two Specified Sampling Strategies SSS and CSS

F-Variate Value	*Sampling Strategy*	
	SSS	*CSS*
$F_{11,11}$	0.71	0.69
$F_{11,88}$	15.87	14.96

From Table 3 we note that the powers of the test in which $F_{11,11}$ is used are less than the corresponding powers of the test in which $F_{11,88}$ is used at both the levels of significance. Thus, prima-facie, there is a case for continuing the present test procedure based on fixed-effects model. However, it is misleading in as much as such a test procedure is insensitive to the situation when null hypothesis is true. As in that case, the first kind of error is also one, which is much greater than what it would be in the former situation. Thus, in the use of the present test procedure, we are likely to arrive at erroneous findings of the kind in which a fertilizer is not superior to the fertilizer currently used, but the present test procedure would show it to be so.

Conclusion 2. It appears from the study of the rejection regions for second kind of error at 5 percent level of significance in Table 4 that the disturbance in the first kind of error should be large, as the regions of rejection in two cases differ a good deal for both the sampling strategies. The test procedure using $F_{11,88}$ arises out of the fixed-effects model approach, whereas the test procedure using $F_{11,11}$ alone or combination of $F_{11,11}$ and $F_{11,88}$ arises out of the mixed-effects model approach. In order to avoid erroneous findings of the kind referred in earlier paragraphs one should shift to the analysis of experiments on cultivators' fields through mixed-effects model approach.

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