REVIEW OF ADAPTIVE SAMPLING DESIGNS

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Abstract: When the population under study is rare and clustered, designing an efficient large area survey is a challenge. Since the survey efforts can be focused on the sub-areas of interest, the adaptive sampling designs are found more appealing in case of such populations. These survey designs can accommodate various types of changes such as changes in the survey objectives, in habitat, in species habitat models etc. Hence these designs are said to offer flexibility in designing a long term survey. There are many examples in environmental science where adaptive sampling designs are used. In this article we review some of the adaptive sampling designs that are useful for sampling from rare and clustered populations. They include adaptive cluster sampling (ACS),
adaptive cluster double sampling (ACDS), negative adaptive cluster sampling(NACS), two- stage negative adaptive cluster sampling (Two-stage NACS), negative adaptive cluster double sampling(NACDS) and two- stage inverse adaptive cluster sampling .

Index Terms- **ACS, ACDS, NACS, Two-stage sampling, Double sampling, Inverse sampling**.

1. INTRODUCTION

For successful environmental management, information on the population is required. It has led to an interest in developing new sampling designs. The designs that are robust for large areas, adaptable for heterogeneity and responsive to change provide a good support for the environmental management. Adaptive sampling designs offer many attractive features for environmental surveys. These designs can be used for surveys of large areas, so that the desired spatial spread and flexibility for responding to heterogeneity is maintained. There are many applications of adaptive sampling designs in environmental science.
While conducting a sample survey, a number of difficult sampling problems are encountered. One of them is the problem in estimating the population mean/total when it is rare or geographically uneven. If the population of interest is hidden or elusive then it becomes difficult to identify it for sampling. The researcher may find the conventional sampling design such as simple random sampling (SRS) stratified sampling etc. as inadequate for producing data from the sampling units while studying such type of population. If conventional sampling designs are applied to population that is rare and clustered then usually very few units possessing the characteristic of interest are selected in the sample. Even a very large conventional sample would be inadequate in such cases. Due to these reasons researchers have thought about the unconventional sampling designs. In this article, we review some of the designs that are useful for sampling from a rare and clustered population.

According to Thompson and Seber (1996), designs that can redirect sampling effort during a survey in response to observed values are known as adaptive sampling designs. The adaptive procedures are also used by French (1993)and Biernacki (1986). These designs use information gathered during the survey to select the succeeding sampling units. This distinguishes adaptive sampling from conventional sampling designs.
In conventional sampling, sampling design is fixed before the study begins. It is based entirely on prior information about the population. In this case the sampling units can be identified before any sampling is actually done. It does not add any sampling units satisfying the condition of interest discovered during the course of sampling. On the other hand, in adaptive sampling the sampling units that are found to satisfy the condition of interest during the survey are added in the sample. The conventional sampling designs are associated with well-established
statistical procedures for making inferences about the population. On the other hand, in adaptive sampling there have been a very few guidelines about obtaining the estimates of population quantities. There has been a significant progress during the last few years in statistical theory for certain adaptive sampling designs. In some cases the estimates based on data from adaptive sampling designs can be more precise than those obtained by conventional designs based on the same amount of sampling effort.
In adaptive sampling, the sampler specifies the:
i) initial sampling design
ii) initial sample size
iii) description of the neighborhood for a sampling unit
iv) condition that initiates adaptive sampling at a sample unit.

The adaptive sampling designs are divided into two groups as:

A) Link Tracing Designs

French (1993)and Biernacki (1986) studies were based on the link tracing designs. Other examples of the use of these designs include studies of cocaine use and associated sexual behaviors (Inciardi, 1993), marijuana and cocaine dealing(Adler, 1990). The general idea of link tracking designs has been identified in the statistics literature. One such variation is network sampling. It is also known as multiplicity sampling. It was introduced by Birnbaum and Sirken (1965).The term “snowball sampling" has been used to a variety of graph sampling (Thompson,1992). Klovdahl (1989) used the term “random walk" to describe a variation of the link-tracing sampling procedure.

B) Other Designs.

i) Sequential Stopping Design

Adaptive sampling designs include sequential stopping designs. In these designs the sampling continues till a given criterion is attained. The procedure may be based on sequentially observing the variable of interest and evaluating the criterion as unit is selected or it may be based on batches of units.

ii) Adaptive Allocation Design

In this design first a sample is obtained by using a conventional design. This sample is then examined for some pre- fixed condition related to the observed values of the variable of interest. Sampling is then concentrated in those areas.

Thompson (1990) introduced ACS and used it for surveying rare and clustered population. It is discussed in Section 2 of this article. This design suffers the drawback of losing control on the final sample size. To overcome it Medina and Thompson (2004) introduced adaptive cluster double sampling (ACDS). It is a method based on combining the idea of double sampling and ACS. It is reviewed in Section 3. This design requires the availability of an inexpensive and easy to measure auxiliary information. It completely ignores the type of relationship between the auxiliary variable and the variable of interest. If the relationship is negative then negative adaptive cluster sampling (NACS) can be used. It is proposed by Latpate and Kshirsagar (2018a) and is discussed in Section 4. In Section 5 and 6 variations of NACS viz: Two-stage NACS and negative adaptive cluster double sampling (NACDS) proposed by Latpate and Kshirsagar (2018b) and (2018c) are discussed. Section 7 explains the procedure of Two- stage inverse adaptive cluster sampling proposed by Latpate and Kshirsagar (2018d). Section 8 discusses the results and conclusions relating to the designs introduced in the earlier sections.

2. ADAPTIVE CLUSTER SAMPLING (ACS)

In this sampling design an initial sample is selected with a conventional sampling design. Whenever the variable of interest satisfies a specified condition for an individual unit in the sample, units in the neighborhood of that unit are added in the sample. Further, if any of the added units satisfy the condition, still more units in its neighborhood are also added in the sample. This is continued till no further unit in the neighborhood satisfies the required condition. In this method neighborhoods can be defined by social or institutional connection as well as geographically.

Thompson (1990) presented designs in which, whenever the observed value of a selected unit satisfies a condition of interest, additional units are added to the sample from the neighborhood of that unit. He calls such a design as an adaptive design. The basic idea of these designs is illustrated in this paper. A design such as illustrated in this article differs from classical sampling designs. In these designs the selection procedure depends on observed values of the variable of interest. The theoretical advantages of these designs were discussed by Basu (1969) and Zacks (1969). In ACS, the final sample size is variable. Considering it as a random variable Latpate et al. (2018e) have derived expression for the expected final sample size under ACS.

In this design, an initial simple random sample(SRS) is selected with or without replacement. When a selected unit satisfies the condition, all units in its neighborhood are added to the sample and observed. For any of those units that satisfy the condition, the units in their neighborhoods are added to the sample. Thus the procedure is continued till no further element can be added in the sample. Collection of all units that are observed under the design as a result of initial selection of a unit is termed as a cluster. A sub collection of units within each cluster is called as a network. It has the property that selection of any unit within network would lead to inclusion in the sample of every other unit in the network. Any unit not satisfying the condition but in the neighborhood of one that does, is termed as an edge unit. The selection of edge unit does not result in the inclusion of any other units. Any unit included in the initial sample that does not satisfy the condition is considered as a network of size one. Thus the population may be uniquely partitioned into networks.

Thompson (1990) has discussed four unbiased estimators of the population mean in this paper.

It is easier to understand any methodology with the help of an illustrative example. We consider an example by Edgar Barry Moser to illustrate methodology of ACS. Suppose that a scientist is studying a particular weed that grows in strawberry fields. The weed is not particularly abundant, but serves as a host plant for a disease of strawberries. The scientist would like to estimate the total (or average) number of weeds in the field using adaptive cluster sampling.

The scientist divides the field using a grid system to produce contiguous sampling units. The following Fig. 2.1 shows the hypothetical strawberry field divided into sampling units using a grid. The numbers in the squares of the grid indicate the number of weeds identified in the corresponding sampling unit. The absence of any number in the square indicates the absence of weeds in that sampling unit. The scientist initially takes a simple random sample without replacement of10 sampling units. These are shown in the Fig. 2.1. It is required to specify a condition for searching the neighborhood. Here, the specified condition; where is the number of weeds present in the i^{th} sampling unit. By using the procedure of adaptive cluster sampling, the final sample of units is obtained and shown in the Fig.2.2.After obtaining the final sample, the sampled networks are identified. A network consists of the initial sampling unit and any other sampling units in its neighborhood meeting the specified condition that are identified through the adaptive sampling process. The initial units that do not have the weed present are considered as networks of size 1.denotes the total number of weeds observed in the ith network.

From the above initial sample of units; 9 distinct networks are identified.

One network has units with weeds.The second has with. The remaining 7 networks have oneunit each with zero weeds. That is, and , for

Using these values the inclusion and intersection probabilities are computed.These probabilities further can be used to obtain the estimate of the total/average number of weeds and variance of this estimate.

				1					
	2	15	8	1		*		*	
	1*	2	*						
						2			
*		*			7	*10			
					7	*3			
				*	1				
		5	2						
	1	9						*	

Figure 2.1: Hypothetical strawberry field divided into sampling units using a grid. Initial sampling units represented by * in those units.

				1					
	2	15	8	1		*		*	
	1*	2	*						
						2			
*		*			7	10*			
					7	3*			
				*	1				
		5	2						
	1	9						*	

Figure 2.2: Final sample of units obtained by adaptive procedure.

3. ADAPTIVE CLUSTER DOUBLE SAMPLING (ACDS)

Although, the ACS design is found appropriate for sampling from a rare and clustered population, it suffers from drawback of losing control of the final sample size. Several suggestions have been made by the different researchers for limiting this final sample size of adaptive cluster sample. For instance, Salehi and Seber (1997)suggested a two stage sampling design in which primary units are selected using a conventional design and secondary units within the selected primary units are sub sampled using ACS. Brown (1994) proposed a design in which initial sample is selected sequentially until the final sample size reaches a specified value. Lee (1998) developed a two phase design, in which the first phase sample is an ACS sample based on an auxiliary variable and the second phase sample is selected from the first phase using probability proportional to size (PPS) with replacement sampling design. This design controls the number of measurements of the study variable but it cannot control that of the auxiliary variable. Salehi and Seber (2002) proposed an estimator of the population mean. Bahl and Tuteja (1991) proposed ratio and product type exponential estimators for estimating the mean of a finite population. Medina and Thompson (2004) proposed a multiphase variant of ACS. It is obtained by combining the ideas of double sampling and ACS. It is

called adaptive cluster double sampling (ACDS). In this design an auxiliary variable which is easy to measure and is inexpensive is considered. This variable is used to select the first phase ACS. The network structure of this first phase sample is used to select the subsequent subsamples, which are selected using conventional design. Values of the variable of interest, associated with the units selected in the final phase subsample only are recorded and the population mean is estimated by a regression type estimator. The ACDS allows the sampler to overcome the drawbacks of ACS.

Procedure of ACDS

Let denote the finite population of units. andare the variable of interest and auxiliary variable respectively. The values of and associated with are denoted by) for. Suppose that no information is available about the auxiliary variable before starting the sampling stage. It is required to estimate the population mean of y -values.

In the first phase of ACDS, an ordinary adaptive cluster sample based on the values of is selected. For that purpose the procedure given by Thompson (1990) is used. Here indirectly, it is assumed that condition relatedto variable for additional sampling and the neighbours of each unit of are well defined. These definitions form a partition of into networks.

Let denote the initial sample that is used to select adaptive sample.

Let be the size of.In the second phase, the sample is selected by using conventional methodcontaining networks from the different networks intersected by. If is selected with replacement then the number of distinct networks in may be less than. These networks are denoted by networks.

The third phase consists of selecting a conventional subsample of units from each of the distinct networks in . Further, the y -values associated with every unit in these subsamples are recorded. The subsamples of units are denoted by ; and they are assumed to be independently selected.

In this procedure, the value associated with every unit in the adaptive cluster sample has to be measured. Hence, the procedure does not controlthe number of measurements of the auxiliary variable but that of the variable of interest only. The measurements of the auxiliary variable are easy and inexpensive. Hence, one can use a relatively large initial sample which increases the probability of intersecting networks with units satisfying the condition and that improves the efficiency of the estimators. Using this method, Medina and Thompson (2004) have proposed a regression type estimator of the population mean of Y . It is same as that presented in Srndal et al. (1992, p. 364) for the regression estimator used in two-phase sampling.

4. NEGATIVE ADAPTIVE CLUSTER SAMPLING (NACS)

If and are positively correlated then we do not get abundant auxiliary information because the population under study is rare and clustered. Hence, ACDS cannot be used in such situation. Felix and Thomson have completely ignored this point. Irrespective of the type of relation between the auxiliary and interest variable, they have suggested the use of ACDS. If we have a rare and cluster population with respect to the variable of interest then to have an abundant auxiliary variable there must be a strong negative correlation between the two variables. Gattone et al. (2016) proposed adaptive cluster sampling for negatively correlated variables. They did not utilize the auxiliary information at design stage. But, they used it at estimation stage.

Latpate and Kshirsagar (2018a) presented negative adaptive cluster sampling (NACS). This method assumes a high negative correlation between the variable of interest and the auxiliary variable. It also assumes the availability of complete information on the auxiliary variable. This design uses the auxiliary information at the design as well as estimation stage.

Procedure of NACS

Form a grid of population containing grid points of equal size and shape.Draw an initial sample of size grid points from this grid using simple random sampling without replacement (SRSWOR) or simple random sampling with replacement (SRSWR) method. Check whether each of the selected units satisfies the condition or does not satisfy the condition. Add the unit to the left, right above and below to each unit included in the initial sample that satisfies the condition . These units are called neighborsof that unit. If any of these neighbors satisfy the condition , add theirneighbors also to the sample. Continue this way till the neighbors that don't satisfy the condition are found. The set of neighbor units satisfyingthe condition along with the corresponding unit selected in the initialsample that satisfies the condition constitutes a network. Thus, the networks are formed around the units selected in the initial sample that satisfy. Note that a unit selected in the initial sample which does not satisfy

the condition forms a network of size one. Suppose distinct clustersare formed with respect to population. A cluster includes the units in a network and the corresponding edge units. Edge units do not satisfy the condition . If all edge units in a cluster are dropped we get a network. From the clusters, we get the networks. The values of the variable of interest corresponding to all the units in these networks are observed. The authors have proposed modified ratio type, modified regression type and exponential product estimators of the population total of the variable of interest. Latpate and Kshirsagar (2018a) have explained the procedure of NACS with the help of sample survey.

5. TWO-STAGE NEGATIVE ADAPTIVE CLUSTER SAMPLING (TWO-STAGE NACS)

Latpate and Kshirsagar (2018 b) proposed two-stage negative adaptive cluster sampling design. It is a combination of two-stage sampling and negative adaptive cluster sampling (NACS) designs. In this design, they consider an auxiliary variable which is highly negatively correlated with the variable of interest and auxiliary information is completely known. In the first stage of this design, an initial random sample is drawn by using the auxiliary information. Further using Thompson's (1990) adaptive procedure, networks in the population are discovered. These networks serve as the primary stage units (PSU's). In the second stage, random samples of unequal sizes are drawn from the PSU's to get the secondary stage units (SSU's). The values of the auxiliary variable and the variable of interest are recorded for these SSU's.

The authors have proposed Composite Horvitz-Thompson and two-stage regression estimators of the population total of the variable of interest.

6. NEGATIVE ADAPTIVE CLUSTER DOUBLE SAMPLING (NACDS)

Latpate and Kshirsagar (2018c) have proposed a new method for estimating the mean/total of the variable of interest. If all information on auxiliary variable is available and the two variables are negatively correlated then this new method is proposed. It is known as the negative adaptive cluster double sampling. This method is a two phase variant of the NACS obtained by combining the idea of the double sampling and NACS. It is a cost effective method. To exploit the auxiliary information at design and estimation stage; auxiliary information must be available, easy to measure and less costly.This design is generalization of NACS when the population parameters of auxiliary information are unknown.

Procedure of NACDS

An initial sample of size units is drawn from the population by using SRSWOR.Denote this initial sample drawnas. From, obtain an adaptive cluster sample by using Thompson's procedure. Let denote the number of distinct clusters formed by. Mark the corresponding clusters in the population and drop down the edge units to get networks. This completes the first phase of the design.

From each of these selected networks draw a sample by using SRSWOR. The sizes of these samples may be different. Suppose denotes the number of units selected from the th selected network. Collection of all these units selected be denoted by.This completes the second phase of sampling design. Now, note the values of andfor all the units included in. This data is used to estimate the population parameter. The authors have proposed new ratio, regression and product type ratio HT estimators of the population total of the variable of interest.

7. TWO-STAGE INVERSE ADAPTIVE CLUSTER SAMPLING

Inverse sampling for attributes was introduced by Haldane (1945). In this method the sampling continues till a predetermined number (say) of units possessing the attribute has been drawn. Haldane obtained an unbiased estimator of the population proportion of units possessing the attribute. Sampford (1962) introduced the inverse sampling with unequal probabilities. Pathak (1964) showed that this method of sampling is equivalent to sampling with unequal probabilities without replacement in some sense. Lan (1999) has shown that the usual estimators based on fixed sample size are biased when inverse sampling is performed. Christman and Lan (2001) considered estimators of the population total based on inverse sampling. They considered inverse sampling with stopping rules based on controlling the number of rare units sampled from the population. They named this design as inverse adaptive cluster sampling. It is a sequential sampling design in which an adaptive component is added. Salehi and Seber (1997) introduced two stage adaptive cluster sampling. In this method the population is divided into a number of primary units and each of these units is further divided into a number of subunits. At the first stage of sampling, a number of primary units are drawn using simple random sampling method. From each of these units, a predetermined number of subunits are drawn in the second stage of the sampling method. Further, the ACS method is used to select the neighboring subunits of the selected sub units. Salehi and Smith (2005) discussed a two stage sequential sampling method which is neighborhood free adaptive sampling procedure. In this method, a sample of primary units is selected by some conventional sampling design and then a subsample of secondary sample units within each selected primary unit is drawn. For estimating the total of a large population which is divided into clusters that contain units of unequal sizes, Latpate and Kshirsagar (2018c) proposed a new method and named it as the two-stage inverse adaptive cluster sampling.

Procedure of two-stage inverse adaptive cluster sampling

Consider a large finite population of units that is divided into non-overlapping clusters which serve as PSUs. Let denote the size of the u^{th} cluster, () so that we have

.

At the first stage, a random sample of clusters is drawn from the clusters in the population by some design with inclusion probability for the unit and joint inclusion probability for primary stage units and.

At the second stage, a random sample of , () units is drawn by using simple random sampling without replacement from the selected u^{th} cluster so that is the total initial samplesize. Each of the selected units is checked with respect to the condition.

If at least units satisfying condition are found in thissample of units then the sampling is stopped. Otherwise it is continueduntil either

exactly units from are selected or (a pre-fixed number)units in total are selected from the th cluster where . If a unit selected from the th cluster satisfies then the correspondingnetwork is completely included in the sample by using Thompson's (1990) procedure of adaptation. Here is the number of successes (that is, units satisfying the condition) which
is proportional to the sizes of selected clusters at the first stage.

Where, is the total number of units satisfying the pre-decided condition .is the draw by draw selection probability of the th cluster.
The authors proposed an unbiased estimator of the population total based on Murthy's estimator.

8. RESULTS AND CONCLUSIONS

A pilot study was conducted by using ACS. It was observed that the final sample size in ACS is much more than simple random sampling without replacement (SRSWOR). Thus ACS loses control on the final sample size. Since the expected sample size under ACS is the total size of the included clusters for the variable of interest and expected effective sample size under NACS is the total size of the included networks for the variable of interest, the effective sample size in NACS is smaller than the final sample size in NACS. Expected cost of sampling in ACS is given by

the product of cost of inspection per unit and the expected final sample size. Expected cost of sampling in NACS is the sum of two components. First is the cost of sampling with respect to auxiliary variable and the second is the cost of sampling with respect to variable of interest. Since the cost of taking observation on the auxiliary variable is lesser as compared to that of the variable of interest, finally the expected cost of sampling in NACS becomes smaller than ACS. Thus NACS is cost effective. If we use the same estimator in ACS and NACS, the two designs are equally efficient because the two designs differ only at the design stage. The degree of correlation between the auxiliary and the interest variable affects the performance of NACS. If the two variables are positively correlated then NACS reduces to ACS. Modified regression estimator is more efficient than the modified ratio estimator. The modified regression estimator in NACS gives better results as compared to its use in ACDS and ACS. This estimator is found to be more efficient than the conventional regression estimator in SRSWOR. In NACS, product estimator is superior to modified ratio estimator and inferior to modified regression estimator. NACS assumes that the values of the auxiliary variable corresponding to all units in the population are known. For large geographical areas, it is very difficult to get such information. It limits the applicability of NACS.
In ACDS the second phase units are selected by using some conventional sampling technique and hence the sampling variations are introduced in the second phase as well. Due to this the standard error (SE) of the estimator is increased. On the contrary, in NACS, there are no second phase units. We take observation on all the units included in the final adaptive sample. So, sampling variations introduced in ACDS at the second phase are completely wiped out in NACS. Hence NACS performs better than ACDS. Sampling efforts are reduced in NACS as compared to ACDS.
Expected Sampling Cost in ACS > Expected Sampling Cost in NACS > Expected Sampling Cost in NACDS. Thus the new design is cost effective as compared to NACS and ACS. Also, NACS estimator is more precise as compared to NACDS. The regression estimator is more precise as compared to ratio estimator for NACDS. If the estimators used in NACDS and ACDS are same then in terms of precision, both the methods are equally efficient.
The expected final sample size in ACS > expected effective sample size in NACS > expected effective sample size in two-stage NACS.
The modified regression estimator in two stage NACS was found to be more precise than the Composite HT estimator used in two-stage ACS and the regression estimator used in ACDS.
It was observed that, the cost of sampling in two-stage NACS < cost of sampling in NACS < cost of sampling in ACS. Thus the proposed two-stage NACS design is cost effective as compared to the other existing designs applicable for the rare and clustered populations. When the gathering of information on the auxiliary variable is possible and inexpensive and there is negative correlation between the two variables; two-stage NACS can be recommended. The empirical sample size remains constant for the increase in the number of successes (r) in case of two stage inverse adaptive sampling, but it shows an increase in case of inverse adaptive sampling. The empirical sample size is found to be consistently smaller in two-stage inverse adaptive sampling than that in inverse adaptive sampling. The estimator used in two stage inverse adaptive sampling is observed to be more stable than that in inverse adaptive sampling. Two - stage adaptive cluster sampling has lesser sample size. Hence, this method is cost effective.

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