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Sampling for Thematic Map Accuracy Testing

Stratified systematic unaligned sampling and an additional random sample of points for under-represented categories are employed.

Introduction

This paper concerns evaluating the accuracy of thematic content for all types of thematic maps such as forest type maps, soil survey maps, geological maps, vegetation maps, and land use and land cover maps. Statistical procedures applicable to this evaluation include techniques for sampling and determining accuracy. This paper contains a discussion of these procedures and references an application of their use.

Abstract: *The minimum sample size needed to validate the accuracy for each category with specified confidence is developed from the cumulative binomial distribution. The critical level developed also from the cumulative binomial distribution is used as the criterion to determine if the identification from remotely sensed data of a thematic category meets a specified accuracy. The algorithm for selecting a sample for thematic map accuracy testing uses (1) a stratified systematic unaligned sampling technique based on the map as a whole, and (2) an additional random sample of points for under-represented categories from all points in that category. A computer program has been prepared to select the sample based on the Geographic Information Retrieval and Analysis System (GIRAS) file. The computer program compares the category classifications interpreted from remotely sensed data to the field identified classifications and lists the statistical and tabular results of this comparison. The estimated overall accuracy of the map, and the estimated accuracy for each category on the map, are considered with associated confidence limits.*

The thematic map is divided into regions called polygons, according to the categories of the theme as determined by imagery. A number of test points which have been selected in the polygons of each category is called a sample. The interpreted category at the test points is compared with what is known from investigations on the ground. The data thus acquired result in a set of agreements and disagreements between the categories determined by ground investigation and the categories determined by image interpretation or digital classification. This set is analyzed to determine the accuracy of interpretation or classification. A value of 1 is given to a successful classification of the test point, and a value of 0 given to an unsuccessful classification. The binomial distribution gives a formula for the probability that the sample contains exactly a certain number of successful classifications.

Background

Evaluating the accuracy of a thematic map requires sampling statistically the classified polygons to determine if the thematic categories, as mapped, agree with the field-identified categories.

Berry (1962) used the stratified systematic unaligned sampling procedure to select samples in similar type studies and has recommended this procedure (Berry and Baker, 1968, pp. 91-100) for

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use in accuracy testing of the land-use and land-cover maps produced by the U.S. Geological Survey. Cochran (1977, pp. 227-228), in discussing systematic sampling in two dimensions, states that it has been found that the square grid had about the same precision as simple random sampling in two dimensions; and that the unaligned pattern within the square grid will often be superior to both a systematic pattern within the square grid and to stratified random sampling. He cites (p. 221) Matern (1947) as proposing this function as a model for the natural populations for forestry and land-use surveys. Systematic sampling distributes the sample units equitably over the entire region of interest, and may be treated as if it was random, provided that systematic effects in the population are made ineffective by the sampling (Freund and Williams, 1972, p. 416).

Experience, however, has shown that this technique is clearly area weighted (Fitzpatrick-Lins, 1981). That is, most of the sample points are selected in those categories that cover most of the map area, and the fewest points are from categories that cover the least area. Some small polygons in sparse categories might not be sampled at all. Sampling a limited number of points for some categories would give a poor estimate of the overall accuracy of the map. A sample of the map, with an adequate sample from each category, is needed to represent all categories and to evaluate adequately the overall accuracy of the thematic map.

A method of using the binomial distribution for determining sample size to evaluate the entire map, based upon the confidence interval for the mean, is given by Hord and Brooner (1976). The concept of the confidence interval for proportions is used to determine the sample size when it is desired to define the true mean within certain limits of error. The 95-percent confidence interval may also be used to determine the upper and lower limits of the accuracy of the thematic map, if the sample's accuracy is known, and according to the sample's size. As the sample size increases, the confidence interval decreases. Once the data have been recorded and the sample's accuracy calculated, the confidence limits of the map's accuracy may be determined from a sample of size n. Hord and Brooner (1976) suggest using the lower limit of the confidence interval as an estimate of the accuracy of the map. However, the maps cannot be considered to be any more accurate than the upper limit of the confidence interval.

Van Genderen *et al.* (1978) report that researchers faced with the problem of adequately representing important minor categories on thematic maps have tended to use some form of stratified sampling rather than strictly random sampling. They state that most researchers have adopted a particular strategy without fully describing their methods for selecting sample sizes, the location and areas of sample sites, and the criteria for accepting or rejecting the sites. They conclude by saying that "stratified random sampling techniques have been readily accepted as the most appropriate method of sampling in resource studies using remote sensor imagery, so that smaller areas can be satisfactorily represented. But, the problem still remains on the selection of best sample size for each category." They also state that previous researchers have not provided sufficient justification for the allocation of sample points in each category. They then develop their own procedure and indicate that it was used successfully in their projects.

The procedures developed by Van Genderen *et al.* (1978) use the individual terms of the binomial distribution to express the probability of exactly f errors in x independent binomial trials with probability of error on a single trial equal to p (the probability of making a error). These procedures select the minimum sample size to evaluate a given category when only a few errors are expected, and would be insufficient if the expected number of errors cannot be anticipated. In addition, their procedures do not address the problem of identifying sparse categories on the map and locating the selected sample points in the corresponding polygons.

PURPOSE AND SCOPE

The sampling technique described was developed to correct the deficiencies noted above in sampling to evaluate the accuracy of thematic maps. The work of Van Genderen *et al.* (1978) was published during the early stages of the project, but it was still believed that more work was needed for the reasons stated above. The project was divided as follows: (1) a method was developed to determine the minimum number of sample points to validate the accuracy of any category shown on a thematic map. This method uses the cumulative binomial distribution to express the probability of obtaining at least a minimum number of successes. (2) A critical level of correctly interpreted sample points was developed from the cumulative binomial distribution to determine whether an individual category meets the expected accuracy for the number of points in the sample, with specified confidence. (3) A statistical procedure was developed to express the accuracy of the map on the basis of each category having at least the minimum number of test points. This procedure included an algorithm for the selection of the sample of test points. Finally, (4) a computer program was prepared to select the sample needed to evaluate the accuracy of the map, and to process the comparison data between the interpreted category at the test points and the field identified category, and finally to evaluate the resulting set of agreements and disagreements. Copies of the program are available upon request.

Analysis

Minimum Sample Size for a Category

The theoretical development of the method to determine the minimum sample size to validate the accuracy of any category is based on the cumulative binomial distribution. Let p be the probability that a certain category in a thematic map was interpreted correctly (such a probability, p, will likely vary from category to category). For example: "The minimum level of interpretation accuracy in the identification of land-use and land-cover categories from remote sensor data should be at least 85 percent" (Anderson *et al.*, 1976, p. 5). Therefore, an acceptable accuracy, p, of any category might be 85 percent or greater.

Let x be a random variable such that $x = 1$ for the event that a certain point from this particular category in the map was interpreted correctly, and $x = 0$ for the event that it was interpreted incorrectly. Then x has the probability density function (p.d.f.) for a single observation in a Bernoulli experiment

$$f(x) = p^x(1 - p)^{1-x}, \; 0 \leq p \leq 1, \; x = 0, 1$$

and zero elsewhere.

Then the expected value of x is

$$E(x) = p$$

and the variance of x is

$$\sigma^2 = V(x) = p(1 - p).$$

Suppose we have a random sample $x_1, x_2, \ldots, x_n$ of size n from a certain category with the p.d.f. as stated above. Then the sample sum

$$r = x_1 + \ldots + x_n$$

will have a binomial distribution with mean

$$E(r) = np,$$

and variance

$$V(r) = np(1 - p).$$

Let $\bar{x} = r/n$ be the sample mean. Then the expected value of the sample mean is

$$E(\bar{x}) = p,$$

and the variance of the sample mean is

$$V(\bar{x}) = p(1 - p)/n.$$

Now we will determine the minimum sample size n for a single category on the map that will be needed for estimating the accuracy p of the category. Let E be the error of estimate, the maximum error we can tolerate. We require that the confidence level should be at $\alpha = 5$ percent. Then we have the one-tailed probability

$$P\,(\bar{x} - E \leq p) \geq 0.95. \quad (1)$$

To determine the minimum sample size n for each category of the map, we use the cumulative binomial probability under the assumption that we have some "preliminary estimate" p_0 of the accuracy:

$$P_B = \sum_{r=k(n)+1}^{n} C_r^n p_o^r (1 - p_o)^{n-r} = \sum_{s=0}^{n-k(n)-1} C_s^n p_o^{n-s} (1 - p_o)^s \quad (2)$$

where p_0 is an estimate of p from a former experience, and

$k(n) = [n(p_0 + E)]$ = the largest integer less than or equal to $n(p_0 + E)$.

The minimum sample size n is determined to be the smallest integer n such that

$$P_B \leq 0.05.$$

Solution for n is effected for given values of p_0, α, and E. Thus, Table 1 represents the minimum sample size n for a single category at the 95 percent confidence level for various assumed values of p_0, and for $E = 10$ percent.

Given the preliminary estimate p_0 for the expected accuracy of each cateogry, a computer program based on the solution for the cumulative binomial probability can be used to calculate the minimum sample size n for each category. For example, for those categories with the assumed p_0 $\geq$85 percent, the minimum sample size n would be 19 with $E = 10$ percent, with 95 percent confidence.

Testing Accuracy for a Category

The theoretical development of the method to determine whether a given category meets the expected accuracy value for the number of points in the sample, with specified confidence, is based on the cumulative binomial distribution. The critical level is defined as one less than the minimum

Table 1. Minimum Sample Size, n, for a Single Category at the 95 Percent Confidence Level for Various Assumed Values of P_0, and for E = 10 Percent

P_0	n
0.50	60
0.55	57
0.60	60
0.65	52
0.70	45
0.75	40
0.80	30
0.85	19

number of points which must be correctly interpreted from any given sample in order to accept the hypothesis at a given significance level that the category is interpreted within the tolerance for the specified accuracy. When the number of correctly interpreted sample points for the category is larger than the critical level, for a given sample size, the category accuracy equals or exceeds the expected limit with some predetermined probability.

Test 1.

$$H_0 : p \geqslant p_0 = 0.85$$
$$H_1 : p < p_0$$

Choosing our test level as $\alpha = 0.05$, we wish to find the largest integer c such that

$$P(r \leqslant c \mid p = p_0) \leqslant 0.05,$$

i.e.,

$$\sum_{r=0}^{c} C_r^n p_0^r (1 - p_0)^{n-r} \leqslant 0.05.$$

c is the critical level and we reject H_0 at the 5 percent level, if $r \leqslant c$. The chances of rejecting the hypothesis H when it is true are no more than 5 percent, on average.

THE CRITICAL LEVEL c OF TEST 1

Sample size n	Critical level c
10	6
15	9
20	13
25	17
30	21
35	25
40	29
45	33
50	37
55	41
60	45

For example, for the sample size $n = 45$, we will reject the hypothesis $p \geqslant 0.85$ at 5 percent level when the sample mean $\bar{x} \leqslant c/n = 33/45 = 73.3$ percent.

Test 2.

$$H_0 : p < 0.85$$
$$H_1 : p \geqslant 0.85$$

We wish to find the smallest integer c such that

$$P(r \geqslant c \mid p = 0.85) \leqslant 0.05,$$

i.e.,

$$\sum_{r=c}^{n} C_r^n p^r (1 - p)^{n-r} \leqslant 0.05.$$

We reject H_0 (i.e., accept $H_1 : p \geqslant 0.85$) if $r \geqslant c$, c being the *critical level*. The chances of our accepting the accuracy $p \geqslant 0.85$ when it is false are no more than 5 percent, on average.

THE CRITICAL LEVEL c OF TEST 2

Sample size n	Critical level[1] c
10	11
15	16
20	20
25	25
30	29
35	34
40	38
45	43
50	47
55	52
60	56

[1] The critical level values for test 2 are similar to those determined by Ginevan (1979) in developing his tables of optimal sample size.

For example, for the sample size $n = 45$, we will reject the hypothesis $p < 0.85$ (i.e., accept the hypothesis $p \geqslant 85$) at 5 percent level when the sample mean $\bar{x} \geqslant 43/45 = 95.6$ percent.

ACCURACY OF A THEMATIC MAP

The accuracy of a thematic map has been a very complex issue both in definition and measurement. For a polygon to be interpreted correctly, both its boundary and its classification must be correct. The accuracy can be expressed in at least two ways, either by the probability E_1 that any randomly selected point on the map is classified correctly (expressed as a percentage of area) or by the ratio E_2 of the number of polygons in the map that have been interpreted correctly to the total number of polygons in the map (expressed as a percentage of the number of polygons). These two measures of accuracy can be expressed by the formulas:

$$E_1 = A^1/A, \quad (4)$$

where A is the total area shown by the map and A^1 is the area with correct interpretation, and

$$E_2 = R/N, \quad (5)$$

where N is the total number of polygons in the map and R is the number of polygons with correct interpretation. These two accuracy measures have their advantages and disadvantages, depending on the users' needs. For some particular maps, such as those having one predominant category with an intermixture of several small polygons in different categories, these two accuracy measures differ greatly. Therefore, a carefully planned sampling procedure must be adopted to incorporate the advantages of both, before conducting a field test.

To simplify quantifying the accuracy of area data, point data are used as a surrogate for area data. The total number of points selected would be representative of the total area of the map, and the number of points correct would be representative of the area of correct interpretation. The analysis is then based on point data rather than on area data as given in Equation 4. The resulting percentage of correctly classified points is an estimate for the accuracy of the map as a whole but not for the accuracy of the classification of individual categories. An adaptation of Equation 5 is necessary to determine the accuracy of all categories shown on the map. Not every polygon need be sampled, as in Equation 5, but every category should have the necessary number of points sampled to provide a reliable estimate of accuracy. A composite of these two measures of accuracy, therefore, using point data as a surrogate for area data, can provide a reliable estimate of map classification accuracy.

Overall accuracy based on total sample points. In the classical method of estimating the accuracy of a thematic map, the overall accuracy is the ratio of the number of correctly interpreted sample points to the total number of sample points, expressed as a percentage. This ratio is derived from an area-weighted sampling technique such as some form of stratified systematic sampling in two dimensions. The overall accuracy E_1 is

$$E_1 = \left(\sum_{h=1}^{k} r_h\right) \Big/ \left(\sum_{h=1}^{k} n_h\right), (h = 1, 2, \ldots, k) \quad (6)$$

where the numerator is the number of correctly interpreted points and the denominator is the total number of points sampled. This equation is the same measure of accuracy as Equation 4, because point data are a surrogate for area data if the sampling procedure used is area-weighted. It has been stated above that experience has shown that the stratified systematic unaligned sampling procedure is area weighted and, thus, is a good surrogate for area data. However, this measure of accuracy must be presented with its lower and upper confidence limits, determined at a specified confidence probability (say 95 percent).

Overall accuracy based on stratified sampling. The sampling algorithm developed in this project has augmented the sample obtained by the area weighted method—the stratified systematic unaligned sampling procedure—with additional sample points in the sparse categories so that there is at least the desired minimum number of points in each category. This amounts to sampling in two frames (A and B), where frame A is the area of the map and frame B is the list of interior points for each category.

Because the selected sample now has additional points for the sparse categories, the sample is no longer area-weighted. An accuracy value computed as the simple average would give undue weight to these sparse categories in an overall value for the map. It is therefore necessary to weight the individual category accuracies by the proportion of its area in order to again achieve an area-weighted overall accuracy value.

The accuracy of each category of classification is based on the estimate of the population total $\hat{Y}$ when sampling from two frames (Raj, 1968, p. 254; Cochran, 1977, p. 164). The equation has the form

$$\hat{Y} = N_a\ (y_a/n_a) + N_b(y_b/n_b) + f(N_{ab}) \quad (7)$$

where

N_a, N_b = numbers of points in populations of sampling frames A and B, respectively, for category h.

N_{ab} = number of points belonging to both A and B (since the chance of sample points belonging to both A and B is very slight, the equation is shown in functional form and is ignored in calculation).

n_a, n_b = sample size from frames A and B for category h.

y_a, y_b = number of points correct from samples A and B for category h. The population proportion for category h is then:

$$P_h = \hat{Y}_h/(N_a + N_b)_h. \quad (8)$$

In this procedure, where each category has at least the desired minimum number of sample points, each category can be considered to be a stratum. According to Snedecor and Cochran (1967, p. 526), the estimate of the stratified population proportion p_{st} is

$$p_{st} = \sum_{h=1}^{k} W_h\ p_h \quad (9)$$

where p_h is the population estimate in stratum h, and W_h is the stratum weight. For an area weighted accuracy estimate, the weight W_h is the ratio of the area of the h^{th} category to the total area of the map. Furthermore, this single accuracy value is not, in itself, sufficient. The accuracy and confidence limits for each category in the map should also be reported as a table in the marginal information on the map.

The variance for $\hat{Y}$ is given approximately by (Raj, 1968, p. 254)

$$V(\hat{Y}) = \frac{N_A^2}{n_a}\ v(p_a) + \frac{N_B^2}{n_b}\ v(p_b) \quad (10)$$

where

$$v(p_{ab}) = [p(1 - p)/n]_{a,b}$$

for each caegory h, and the variance for p_h is by error propagation,

$$V(p_h) = [1/(N_a + N_b)_h]V(\hat{Y}_h). \quad (11)$$

Also, according to Snedecor and Cochran (1967, p. 527), the estimated variance of the estimate of the mean is

$$V_{st} = \sum_{h=1}^{k} W_h^2 V(p_h). \qquad (12)$$

Since the sample size for the entire map is large, the estimated mean will be approximately normally distributed, and the confidence limits about the accuracy value will be (Snedecor and Cochran, 1967, p. 527)

$$L = p_{st} Z_{\alpha/2} \sqrt{V_{st}}. \qquad (13)$$

where $Z_{\alpha/2}$ is the standard normal deviate for the desired probability level $1 - \alpha$.

When evaluating the accuracy value for an individual category, the confidence limits about that accuracy value should be considered, based upon the number of points in the respective sample. The confidence limits indicate the interval which contains the true percentage in the sampled population, with some pre-established confidence value. Hord and Brooner (1976) give a table of the upper and lower 95-percent confidence limits for sample sizes of 50 to 400 (in steps of 50), and for accuracy values from 80 percent to 100 percent, although they neglect to apply the "correction for continuity" (Snedecor and Cochran, 1967, pp. 209-213).

For sample sizes in excess of 30, confidence limits which include the correction for continuity may be computed from the normal approximation (Snedecor and Cochran, 1967, p. 31 and pp. 210-211).

For sample sizes of 30 or less, exact confidence limits are computed from the binomial distribution. A table for the 95 percent and 99 percent confidence interval for the binomial distribution is given in Snedecor and Cochran (1967, pp. 6-7).

Application Sampling Algorithm

Selection of the sample for accuracy testing the thematic map is expedited if the map information is contained in digital format in a computer data base and is addressable by a computer information system. One computer information system which already exists is the Geographic Information Retrieval and Analysis System (GIRAS) of the U.S. Geological Survey (Mitchell *et al.*, 1977). This system addresses the data bases of the digital land-use and land-cover maps produced under the National Land Use and Land Cover Mapping Program. Another system is the Landsat digital classification system used for computer classification of Landsat digital imagery. The resultant classified pixel information for a given Landsat scene or scenes, or portions of one or more scenes, is the digital data base. The sampling algorithm developed in this project was programmed for use with the digitized polygon-format land-use and land-cover maps in the GIRAS system. A later project will be to program the sampling algorithm for use with the Landsat digital classification system.

An adequate sample for all digitized land-use and land-cover maps may be obtained through access to the GIRAS computer tapes. The initial sample size n_0 may be calculated by such methods as that of Cochran (1977, pp. 75-76, 4.2) in the form

$$n_0 = (Z_{\alpha/2})^2 \, p(1 - p)/d^2 \qquad (14)$$

where p is the expected level of accuracy and d is the desired degree of precision. It is noted that this equation neglects the correction for continuity. The exact confidence limits computed from the binomial distribution are nonsymmetric about the sample mean. Therefore, d should be one half of the confidence interval.

The first approximation to the sample is then selected by the computer using the stratified systematic unaligned sampling method. For the under-represented categories (less than the specified minimum number of points for a given category), additional sample points are randomly selected from the list containing one interior point for each polygon recorded on the GIRAS tape.

Finally, the computer compares the interpreted category classifications with the field identified classifications from the accuracy test and lists the statistical and tabular results of this comparison.

Fitzpatrick-Lins (1981) has used the sampling algorithm and computer program in an operational application and has compared the results against a previous accuracy evaluation using a manual sample selection. In the manual sample, "only six of the 26 categories were adequately represented and nine were not represented at all." In the operational application of this procedure, all 26 categories were represented and "an optimum number of points was selected as a minimum unless there were too few polygons in the category to achieve the optimum number." The accuracy of the manual sample was 93 percent, having a one-tailed 95-percent lower confidence limit of 91 percent. The accuracy of the operational application was 97.6 percent with lower one-tailed 95-percent confidence limit of 97.0 percent. (These accuracy and confidence limit values are different from those of the referenced operational paper because of a change in the computer program to account for two-frame sampling. The computer calculations to accept or reject the map as meeting the accuracy criteria were based on an earlier version of the theory paper.)

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