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Statistical Methods for Determining Land-Use Change with Aerial Photographs*

The important parameters to determine are (1) sample square size sufficient to portray landscape complexity, (2) adequate number of samples, and (3) the type of random method to apply.

Introduction

Aerial photographs have long been used to gather information about land use changes (Reeves *et al.*, 1975). The currently popular method of mapping large areas (county and multi-county) by machine processing of Landsat data has provided reasonable detail at level I and sometimes level II land-use classification (Odenyo and Pettry, 1977; Anderson *et al.*, 1976). In this paper, however, our interest is focused on the case where level III or IV statistical information on land use is needed to assess changes over large rural areas; but land-use maps are not needed. Users also need to know how well the mapped data describe the true situation.

Abstract: *Three sampling methods are applied to detection of incipient land-use change occurring over a 337 km² area of Whatcom County, Washington. Techniques for determining accuracy and precision of the three methods are discussed. A 100 percent sample consisting of 130 squares (2.6 km² each) is used as the conceptual population. Parameters within squares are determined with a random grid of 8 dots/km². Simple random, stratified random, and systematic selection of samples from the population are examined. Land-use change between two dates is assessed by paired and unpaired random techniques.*

Paired random samples appear most precise in determining significant land-use changes when compared to unpaired random samples. Systematic selection of samples may result in variable precision depending on whether linear elements or periodicity exist on the landscape. Gains in precision were small when comparing simple random to stratified random sampling. The most useful combinations of the sample square area and dot density within each is either 2.6 km² with 8 dots/km² or 1.25 km² with 15 dots/km².

Goals

The goal of the present study is to evaluate sampling procedures capable of detecting incipient land-use changes in rural areas. These changes result from urbanization pressure on agricultural land and are manifested by encroachment of single family dwellings. These procedures should include

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confidence interval calculation so that real changes may be quantified and separated from "apparent" changes that are due to random errors.

Three specific objectives are to evaluate (1) methods of sample distribution requiring less than total study area coverage, (2) a systematic dot grid sampling method which requires coverage of the whole study area, and (3) the application of the methods under objective 1 to land-use change.

Background

Several authors have described sampling techniques used to collect land-use data from aerial photographs. Berry (1962) reviewed papers on the relative efficiency of several methods, including dot grids and point transects. He reported that, for woodland cover, with four trials of complete coverage dot grids, the expected variance using a simple random distribution of dots was 21.5 times greater than the variance using systematic stratified unaligned dots and 5.65 times greater than arbitrarily stratified random dots. However, in a similar test on a different population he reported variances which, when converted to relative efficiencies, show little difference for six methods of dot distribution. We believe that those variations may be due to the different forms of the populations. Cochran (1977) points out that the variance of a simple random sample will be essentially the same as that of a systematic sample if they are from a population with random order. Other populations may give more precise results with the various forms of systematic samples.

Sloggett and Cook (1967) used Berry's efficiency relationships to design a sampling scheme for land use on a flood plain. They determined the sampling rate necessary to estimate the population mean within ± 5 percent with 95 percent confidence based on a simple random dot distribution spread over 100 percent of the area. Then the dots were distributed by the assumed more efficient stratified unaligned procedure, which uses systematic squares with one random dot in each. A similar procedure was applied by Frey and Dill (1971) for a study of land-use change in the southern Mississippi River alluvial valley. One data point per square mile in a systematic grid was tallied after randomly locating the grid on each photograph. A sample size of 38,000 point observations was used and therefore sampling error was assumed very small.

The validity of considering each data point of a systematic grid as a simple random observation was seriously questioned by Barrett and Philbrook (1970). They indicated that each positioning of the dot grid was one sample regardless of how many data points it had, and that precision was determinable only after many repeated trials. Cochran (1977) agrees with that, as does Freese (1962). Freese goes on to point out that, while it is rather common to see random error calculation formulae used on systematic surveys, experience shows that a few of those surveys will be very misleading.

Bonnor (1975) investigated the possibility of estimating the error of area determinations using single trials with dot grids on simulated forest maps. He pointed out, as did Barrett *et al.* (1970) that, while one could get an area estimate with a single dot grid trial, the error of that estimate was unknown. Not wanting to use repeated trials to establish error, Bonnor investigated factors affecting the error and proposed relationships to calculate it given the characteristics of one trial. He found error (width of the confidence interval) at the 95 percent level was related to grid density, area size, and shape. He developed formulae and graphs to calculate error based on those parameters.

Only one study was found in which less than the entire area of interest was used for sample distribution. Zeimetz *et al.* (1976) calculated land-use change for 53 countries over a period of 10 years using a two-stage area-point scheme. A systematic selection of photographs covering approximately 15 percent of each county was sampled at the rate of 20 random points per mi^2. The basis for selecting this sampling rate was not discussed, but sampling error was defined by calculated coefficients of variability and double sampling four counties.

Study Area

The study area was chosen because extensive ground truth data were available from a previous land-use study. This was conducted to elucidate changes occurring on the agricultural landscape of Whatcom County, Washington (Stepleton *et al.*, 1976). Located in the far northwestern corner of Washington, the study area is bounded by British Columbia, the Georgia Straits, the north Cascades, and the Skagit River Valley (Figure 1). The 337 km^2 portion chosen for this study is known as the Guide Meridian area. It extends from Bellingham to the Canadian border and includes the Nooksack River Valley and adjoining glacial uplands.

Two of the seven data categories from the original study were singled out for discussion in this sampling investigation:

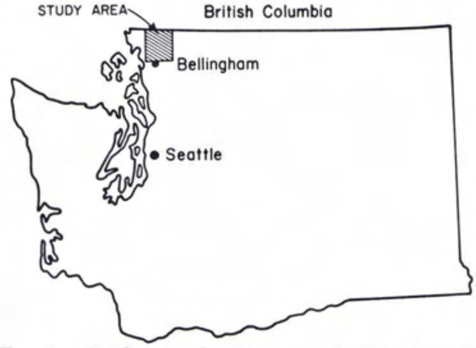

FIG. 1. Study area location in Whatcom County, Washington.

- Hay: Grasses, small grains, clover, and alfalfa are grouped to a high level of management, primarily for livestock feed.
- Cultural features: Nonagricultural features including buildings and yards, transportation facilities, quarries, and industrial sites.

The other five are included in Tables 2, 3, and 6 to show land-use composition of the area. These are:

- Forest and Woodlot: Any area of forest vegetation including trees in fence rows, scattered in pastures, or in dwelling areas.
- Unimproved pasture: Open land with no evidence of intensive management, including grouping areas and idle land.
- Row crops: Includes vegetables, silage corn, and potatoes.
- Berries: All berry crops.
- Water: All lakes, streams, and ditches carrying water.

The hay category was singled out because it covered large areas, and the cultural features category because it exists as small, widely scattered units. These were interpreted from panchromatic photos at 1:65,000 scale for 1974 and 1:20,000 scale for 1966. The land-use category interpretations from the 1:65,000-scale photos were carefully ground checked with land owners, and photo patterns for each land use were studied so that they were easily recognized on the older 1:20,000-scale photos.

Prime agricultural lands were defined for the area by Stepleton *et al.* (1976) as those areas which were known to produce high yields of locally grown crops. The standard Soil Conservation Service definitions were not strictly applied because the required modern soil survey was lacking.

Techniques and Evaluation Procedures

Population Description

Two populations were defined. The first was used to study techniques which involved drawing a sample covering less than the total land area with random dot units called area-point samples. The second was used to study complete systematic area coverage techniques using dot grids. The study area was completely covered with both types of sampling. Since precision of interpretation in this study is comparable across photo scales, and landscape complexity on the ground determines precision of estimates, the results are reported in terms of dot density per unit ground area. All dot densities are given in terms of dots/km^2 and may be multiplied by 2.6 to get dots/mi^2 to enable comparisons with other studies, and for use on photographs of other scales.

Area-Point Samples for Population

A systematic grid of 130 squares with 20 random dots each, fit to the area such that grid boundaries did not coincide with linear landscape features (such as section roads), provided a form of 100 percent coverage which could be used to study various ways of extracting less than a 100 percent sample. The 130 squares are samples from the land-use populations, but constitute all possible samples of that type which could be drawn without shifting the grid. We assume, for experimental purposes, that the 130 squares enumerate conceptual populations and we developed statistics accordingly. The distribution pattern is 13 squares north-south by 10 squares east-west, each covering 2.6 km^2.

The selection of a 2.6 km^2 area with 20 random dots as opposed to some other configuration is based in part on the literature (Zeimetz *et al.*, 1976) and in part on our own investigations. We tried squares representing 5 km^2, 2.6 km^2, and 1.25 km^2 with dot densities of 15, 8, and 4 per km^2. Twenty-five random trials of each combination were conducted on the 1974 photography.

The same grid locations, but different random points, are used on both the 1974 and 1966 photos. The proportion of 20 dots falling in each land-use category provides an estimate of proportion of the land in that category for a particular sample square. Thus, each square gives an estimate of seven populations corresponding to the seven land-use categories.

This procedure is considered a two-stage sampling technique with the 130 squares as a primary sample and the 20 dots/square a secondary one, since variation could originate in each stage. Our efforts, though, were directed toward the analysis of variation due to primary sampling method. Hence, the erros due to secondary sampling are not considered as part of method variability. This is justified for the following reasons:

(1) The variance of the estimate for random samples is dependent for the most part upon the primary sample size, especially if the relative size of the secondary sample is small (Steel and Torrie, 1960). A single sample square is less than 0.8 percent of the total area.

(2) Since all sampling techniques are evaluated on the same 130 squares, the error should not affect relative comparisons between methods. Potential exists, though, for different secondary sample error in comparison between 1966 and 1974 samples, since different random dot patterns are used.

SYSTEMATIC DOT GRID FOR POPULATION

One systematic sample at 98 dot/km^2 was made covering the study area on 1974 photography to determine "ground truth" for systematic dot trials. Four systematic samples, two each at 6 and 2 dots/km^2, were conducted to determine the propriety of Bonnor's method of estimating error. We wish to call these "canvass trials" to differentiate them from the systematic selection of area-point samples.

POPULATION PARAMETERS

Population means, standard deviations, and Fisher's skewness coefficients are used to (1) evaluate, without further sampling, the precision of using various numbers of sample squares; (2) ascertain the validity of assumptions of normality for confidence limit development; and (3) gain an understanding of the distribution of landscape features as reflected in aerial photo interpretations. Table 1 lists these data and defines the populations. Two populations are shown varying by date of photography, prime agricultural land strata, and non-prime strata. Fisher's skewness coefficient (C) shows that some categories are normally distributed (<1) while others are skewed.

AREA-POINT SAMPLING PROCEDURES

Techniques evaluated for distribution of the primary sample are as follows: (1) Systematic sample, (2) simple random sample, (3) stratified random sample, (4) paired random samples for differences between the two dates, and (5) unpaired random samples for differences between two dates.

Simple random sample. For random techniques, population standard deviation, σ, is used to calculate the standard error of the mean, $\sigma_{\bar{x}}$, ie;

$$\sigma_{\bar{x}} = (\sigma\sqrt{n})\ \sqrt{N - n/N} \qquad (1)$$

$$\sigma = \sqrt{[\Sigma_N(x_N - \bar{x})^2]/N} \qquad (2)$$

where n is the number of randomly selected squares and N is the total number of squares (Steel and Torrie, 1960:416). Confidence limits at the 95 percent level are calculated for all random techniques using

$$\bar{x} \pm z_{\alpha/2}\ \sigma_{\bar{x}} \qquad (3)$$

where $z_{\alpha/2}$ is a random variable whose distribution function is approximately that of a standard normal distribution as the sample size, n, approaches infinity. Student's "T" distribution would have been used if populations σ's were unknown. Above about n = 25 the confidence limits are approximately correct even with moderate skewness in the population, i.e., if Fisher's coefficient of skewness, C, is less than 1 (Cochran, 1977).

Stratified random sample. For stratified random sample techniques for selection of squares, $\sigma_{\bar{x}}$ is calculated for the population at a given n by

$$\sigma_{\bar{x}} = \left\{\frac{1}{N^2}\sum_k N_k\ (N_k - n_k)\frac{\sigma_k{}^2}{n_k}\right\}^{1/2} \qquad (4)$$

where n_k = samples in kth stratum,

TABLE 1. POPULATION PARAMETERS μ, σ, AND C

		Populations					
		All lands, N = 130		Prime lands, N = 74		Non-prime lands, N = 56	
		1974	1966	1974	1966	1974	1966
Hay	μ (%)	44.7	43.6	49.3	51.7	38.6	32.9
	σ (%)	21.9	21.5	22.4	17.8	19.5	21.3
	C	0.2	0.2	0.1	0.3	0.0	0.6
Cultural Features	μ (%)	8.1	6.0	9.7	7.1	5.9	4.6
	σ (%)	8.8	6.8	9.2	7.6	7.6	5.3
	C	1.7	1.5	1.7	1.4	1.7	0.9

N_k = population of kth stratum (for this study $N_1 = 74$, $N_2 = 56$), and
σ_k^2 = variance for the kth stratum (Steel and Torrie, 1960:419).

For this study two strata were defined; prime agricultural land [57 percent of the land area] and non-prime land [43 percent of the land area] (Stepleton *et al.*, 1976). For a given sample size covering both strata, the number of samples allocated to each stratum was determined in proportion to the land area. For example, if $n = 26$, $n_1 = 26\ (0.57) = 14.8$ or *ca* 15; $n_2 = 26 - 15 = 11$; where n = total samples $= \sum_k n_k = 15 + 11$.

Systematic sample. Systematic selection of sample squares from our population of 130 squares involved varying the spacing between samples. Sample spacing was calculated by the formula $k = N/n$ where $N = 130$. For example, with a 130 square grid, if a sample size $n = 26$ is desired, there would be five possible unique trials and a sample spacing of $k = 5$. The effects of a particular sample spacing were determined by using all possible trials in each of two directions (N-S, E-W) and generating population and sample standard deviations from these trials.

The applicable formulas are (Cochran, 1977:208)

$$\sigma_{\bar{x}} = \sqrt{\left[\sum_k (\bar{x}_k - \bar{\bar{x}})^2\right]/k} \qquad (5)$$

$$\bar{\bar{x}} = \left(\sum_k \bar{x}\right)/k \qquad (6)$$

k = Number of possible trials for a given sample spacing.
$\bar{x}$ = Mean value for the i th trial at a given sample spacing k.

This $\sigma_{\bar{x}}$ is applicable only for a given sample size, n. Again, since the population is assumed known and these statistics are based on all possible trials, they are population parameters and the term σ and not s is used.

Paired and unpaired random samples. Two methods are used to calculate the minimum requirements for significance of differences between random samples taken on the two dates. The first, unpaired differences, involves testing the hypothesis $\mu_1 - \mu_2 = \bar{d} = 0$ or that there is no significant difference between means. The second involves pairing the random observations at the time of sampling.

For a significant difference with unpaired samples the following must be true (Steel and Torrie, 1960):

$$Z_{calc} = (\bar{x}_1 - \bar{x}_2)/\sigma_{\bar{d}} > z_{\alpha/2} \qquad (7)$$

or

$$\bar{x}_1 - \bar{x}_2 > z_{\alpha/2}\, \sigma_{\bar{d}} \qquad (8)$$

where $\sigma_{\bar{d}} = (\sqrt{(\sigma_1{}^2 + \sigma_2{}^2)/n})\ (\sqrt{N - n/N})$ (9)

and $\bar{x}_1, \bar{x}_2$ are sample means for the two dates. Using σ's from Table 1 for hay and cultural features, we have calculated $\sigma_{\bar{d}}$ (standard deviation of the differences) and the minimum $\bar{d}$ required for significance with representative sample sizes.

Pairing random observations is a method of reducing sample variation in estimating changes in a population (Steel and Torrie, 1960:78). In this case, random pairs are defined to be the same areas on the ground for two different dates. For known populations, $\sigma_{\bar{d}}$ is calculated for any sample size using

$$\sigma_{\bar{d}} = (\sigma_D/\sqrt{n})\ (\sqrt{N - n/N}) \qquad (10)$$

where σ_D is the standard deviation of the paired differences. If populations are unknown, a more complex formula must be used. Differences required for significance of actual populations are calculated as in Equation 7 but the $\bar{d}$ in actual sampling situations is determined as the average differences in sample pairs rather than differences in sample means.

Results and Discussion

The Guide Meridian area is of interest because it typifies rural areas under pressure to provide locations for single family dwellings. Subdivision in the usual sense (many houses built within a short time in a small area), however, is not the method of development. Rather, it is by dispersion of houses throughout the area, making it difficult to determine how much area is affected.

The requirements for a successful enumeration method (in our opinion) are that error is calculable and labor is minimized. Since the 98 dot/km² 100 percent sample was conducted only once, it was not included as a method. It is assumed to represent the land-use composition population for one date as determined by high density grid. The small difference shown in Table 2 between the canvass result and the population means (also 100 percent coverage) is possibly due to using different interpreters and/or different dot densities.

CANVASSES

Canvasses using systematic dot grids require, as Bonnor (1975) indicates, great effort because the data distribution is very intricate and error is difficult to calculate. Use of his method gives 95 percent confidence

TABLE 2. LAND-USE QUANTITIES FOUND ON 1974 PHOTOGRAPHY BY TWO METHODS

Method	Category						
	Hay	Forest	Pasture	Row Crops	Cultural Features	Berries	Water
	%						
Canvass 98 d/km²	41.3	20.2	15.7	8.8	10.2	2.8	1.0
Population mean 130 squares	44.7	19.7	14.7	9.4	8.1	1.5	1.7

limits on maximum expected error for canvass trials. The land-use distribution is assumed to be complex, for which he calculates error by

$$E(\%) = 153.1/(AD)^{0.58} \quad (11)$$

Where A = approximate area of the land use on a map, D = grid density, and E = half the width of the 95 percent confidence interval for maximum error. In this study, four trials of dot canvasses were completed and compared to "true" values. The results of the 98 d/km² canvass are assumed the "true" ground values (Table 2). Two trials with 6 dots/km² and two with 2 dots/km² reveal considerably greater error than the maximum predicted by Bonnor's methods for some land uses (Table 3). For example, using 2 d/km² the hay category shows an absolute difference of error of 3.9 percent of the area for one of the two trials. Bonnor's method predicts a maximum of 2.8 percent of the area as error. Seven of the 14 comparisons made in Table 3 seem to be considerably outside the predicted range. We should expect that only 5 percent are outside the range.

AREA-POINT SAMPLING

Without a method such as Bonnor's we would need repeated trials of canvasses to get measures of error, whereas other sample distribution methods may allow calculation of error. Area-point sampling methods for use on aerial photographs require four decisions about the sample: (1) the amount of area in each square, (2) the within square dot density, (3) whether to distribute the area sample systematically or randomly, and (4) a theoretical number of sample squares.

Sample area and within sample dot density. Others have had apparent success using 20 randomly distributed dots per 2.6 km² area (Zeimetz *et al.*, 1976) and our investigations support this. One is not necessarily limited to that combination, however. In Table 4 are means, $\bar{x}$; standard deviations, s; and coefficients of variation, CV, calculated from 25 reps of each sample area-dot density combination for hay and cultural features.

Analysis of variance shows no difference among means for the hay category. If hay were the only category of interest, one could pick any combination which minimized both CV and labor. We were interested in both

TABLE 3. ABSOLUTE ERROR OF CANVASS TRIALS, 1974 DATA, COMPARED TO MAXIMUM EXPECTED ABSOLUTE ERROR CALCULATED BY BONNOR'S METHOD AT 95 PERCENT CONFIDENCE

Trial	Dots/km²	Category						
		Hay	Forest	Pasture	Row Crop	Cultural Features	Berries	Water
		%						
1	2	3.9	1.2	0.3	2.6	4.1	0.1	1.0
2	2	0.1	2.3	2.0	1.1	1.3	0.1	0.3
Maximum Expected Error		2.8	2.0	1.9	1.6	1.6	0.7	0.9
3	6	0.6	1.2	0.3	1.7	0	0.4	0.1
4	6	1.7	0.2	0.2	1.0	0.6	0.1	0.1
Maximum Expected Error		1.2	0.9	0.8	0.7	0.7	0.3	0.4

TABLE 4. VARIABILITY IN LAND-USE MEANS, STANDARD DEVIATIONS, AND COEFFICIENTS OF VARIATION WITH CHANGES IN DOT DENSITY AND SAMPLE AREA, 25 REPS.

Area	Hay			Cultural Features		
(km^2)	$\bar{x}$	s	cv	$\bar{x}$	s	cv
	%					
			15 d/km^2			
5	45.1	14.5	32.1	14.8	11.9	80.4
2.6	42.2	23.2	54.9	11.5	13.5	117.3
1.25	44.0	25.0	56.8	8.5	5.5	64.7
			8 d/km^2			
5	39.9	13.3	33.3	17.5	20.7	118.3
2.6	44.6	21.4	48.0	11.0	11.1	100.9
1.25	38.8	23.9	61.3	6.4	9.9	154.7
			4 d/km^2			
5	45.2	20.4	45.1	6.8	7.4	108.8
2.6	44.4	28.1	63.3	7.6	10.1	132.9
1.25	46.4	32.0	69.0	8.0	10.0	125.0

land uses, however, and this required some compromises.

The analysis of variance on the cultural feature means showed a significant (99 percent level) interaction between sample area and dot density. Further investigation revealed that, with a sample area of 5 km^2 and either 8 or 15 d/km^2, the means were significantly larger than the other cultural feature means. However, we cannot say that these choices of area-point samples should be eliminated because of the ANOVA result. When compared to our standard (the 98 d/km^2 canvass) by two-tailed t test, they show no significant difference.

The 5 km^2 samples with eight and 15 dot densities were rejected because of additional labor involved in classifying and counting larger numbers of dots. The remaining choice was between the lowest *CV* for cultural features or hay. We chose 8 d/km^2 density and 2.6 km^2 area to be comparable with what others have used; however, we would expect to reduce variation in sampling small features with the 15 d/km^2 density in 1.25 km^2 samples.

Method of sample distribution. Comparisons of standard errors made between three methods, four sample sizes (number of squares), and two land-use categories, representing large area uses (hay, *ca* 40 percent) and small dispersed uses (cultural features, *ca* 9 percent) show efficiencies, $\sigma_{\bar{x}}$, that may be expected (Table 5) (Fowler, 1979, p. 2). Sample numbers are selected to represent a wide range and to approximate integer spacing for systematic samples. Simple random and stratified random results are based on population parameters, systematic results on all possible trials (e.g., 5 trials with n = 26).

Distributing sample squares by systematic means shows marked differences in $\sigma_{\bar{x}}$. Some combinations of sample numbers, numbers of trials, and direction give better results than others; they are inconsistent. This is likely due to some periodicity in the landscape which is picked up by some of the systematic samples. Cochran (1977) points out that this is to be expected with systematic sampling techniques.

The results of trials with systematic distribution of sample squares by direction are of importance because this procedure ap-

TABLE 5. STANDARD ERRORS ($\sigma_{\bar{x}}$) OF THREE METHODS OF ASCERTAINING LAND-USE PROPORTIONS ON 1974 PHOTOGRAPHY, FOR FOUR SAMPLE SIZES

Method	Sample Size (number of squares) n			
	26	32	43	65
	$\sigma_{\bar{x}}$			
1. Systematic (N-S)				
Hay	1.9	2.9	1.5	0.5
Cultural features	1.3	1.5	0.9	0.9
Systematic (E-W)				
Hay	5.4	2.4	1.5	1.7
Cultural features	1.4	0.8	0.9	0.6
2. Simple random				
Hay	3.8	3.4	2.7	1.9
Cultural features	1.5	1.4	1.1	0.8
3. Stratified random				
Hay	3.7	3.3	2.7	1.9
Cultural features	1.5	1.3	1.1	0.8

proximates selecting photos from flight lines. Systematic distribution of area-point windows is easily accomplished by selecting individual photos at certain intervals until the study area is covered. One should not, however, apply this in a blanket manner to all landscapes. The standard errors may be quite variable depending on sample number and land-use distribution.

Stratification of the landscape prior to sampling is often recognized as a means of reducing sample error. One means of stratification to yield information about agricultural land-use change is into prime and non-prime categories. As a trial to determine gains in sampling efficiency, our study area was stratified into prime vs. non-prime land (Stepleton *et al.*, 1976).

Only a very small decrease in $\sigma_{\bar{x}}$ was noted between simple random and stratified random sampling (Table 5). However, if the prime and non-prime strata are treated as separate populations, there is a reduction in σ, with a corresponding reduction in the $\sigma_{\bar{x}}$ at any particular sample size. A reduction in σ is shown on non-prime land in 1974 for hay, row crops, cultural features, berries, and water (Table 6), while forests and unimproved pasture have less variation on prime land. In all cases where efficiency was gained on one strata, it was lost on the other so that overall no gains were made by stratification. The only advantage accrues in reporting data by the desired land-use categories. Reduced variation is likely due to occurrence of these land uses in uniform blocks evenly distributed over the landscape within a stratum.

THEORETICAL SAMPLE SIZE

Confidence interval calculation and sample size determination require a normal population, at least for small sample sizes. Miller and Freund (1965:134) state that for $n > 25$) normality is not required. Thus, we calculated confidence intervals for theoretical sample sizes ($n > 25$) to show what results may be expected for a given method of sampling.

Confidence intervals calculated for simple random sampling are shown in Table 7. These are calculated using Equations 1 and 3. For example, a sample size of 48 is required to achieve ± 2.0 percent about the μ for cultural features and ± 4.9 percent for hay. The required sample would cover 36 percent of the area in this case.

If we draw other data from Table 1, for example, cultural features, 1966 population, and calculate confidence intervals in the same manner, we find the same error levels are reached with 28 samples. This indicates that one should not feel secure using a minimum sample size determined for one date on photography of another date and scale, even though the same area is photographed, if land use patterns have changed.

For small sample numbers ($n < 25$) the population must be normally distributed for calculation of confidence limits. The hay category (1974) is given as an example in Table 8 because Fisher's coefficient of skewness is small (Table 1) and the histogram of the data is bell shaped (not shown). The use of small sample numbers is not recommended unless only a general idea of land-use quantities is needed. The likelihood of showing a real trend in land-use change with these limits is thought to be quite low unless μ is very large and the change is very large.

COMPARISONS BETWEEN DATES

The objective of many land-use studies is to be able to say how much change has occurred between two dates. Without knowing the confidence limits about the mean land-use values for each data, we cannot simply subtract the two means and say the result represents change. The difference may or may not represent change, depending on the method used to determine each mean.

Using our known population, we have calculated differences and $\sigma_{\bar{d}}$ for representative sample sizes and land-use categories using paired and unpaired samples (Table 9). If we used 26 random unpaired sample squares from the population described in Table 1 for

TABLE 6. STANDARD DEVIATIONS, σ, USING STRATIFIED RANDOM SAMPLING, 1974 PHOTOGRAPHY

	Hay	Forest	Pasture	Row Crops	Cultural Features	Berries	Water
				%			
non-prime	19.5	19.8	13.3	6.5	7.6	2.3	2.1
prime	22.4	9.4	11.8	13.0	9.2	6.4	5.9
all-strata	21.9	18.3	13.0	11.9	8.8	5.2	4.8

TABLE 7. 95 PERCENT CONFIDENCE LIMITS, μ, σ, AND SAMPLE NUMBER, FOR 1974 PHOTOGRAPHY, SIMPLE RANDOM SAMPLING

		Hay	Cultural Features
		%	
μ		44.7	8.1
σ		21.9	8.8
n	% of area sampled	±%	
32	25	6.7	2.7
40	30	5.6	2.3
48	36	4.9	2.0
56	43	4.3	1.7
64	49	3.7	1.5

TABLE 8. CONFIDENCE LIMITS CALCULATED FOR NORMALLY DISTRIBUTED DATA, SMALL SAMPLE NUMBERS, 1974, HAY (μ = 44.7)

n	Confidence limits (±%)
8	14.7
12	11.8
16	10.0
20	8.8
24	7.9

1974 and 1966, we would need to find an areal change, d, of 4 percent for cultural features before the change could be termed significant. The confidence limits, ±2 percent, would apply to that difference. If 65 samples were used, a change of 2 percent could be called a significant change and the limits, ±1 percent, would apply. A category with a large standard deviation, such as hay, requires a larger change to be significant and in all cases the $\bar{d}$ required for significance decreases as sample size increases. If we used paired samples with the cultural features category and 65 sample differences, the minimum $\bar{d}$ for a real change is 1.4 percent. Less difference is required here than with the unpaired samples (which is 2 percent). If we were satisfied with a 2 percent minimum areal change, we would expect to find a significant difference with 43 paired samples, as opposed to 65 samples with the unpaired method.

Another way of visualizing gains in efficiency using sample differences may be to assume, for example, that Table 1 contained sample means (instead of population means) found by simple random methods and that we are interested in what changes have occurred with cultural features in the study area.

The means of 6.0 (1966) and 8.1 (1974) would have confidence intervals of ±1.2 and ±1.5 respectively, calculated by Equations 1 and 2 for N = 130, n = 65, σ's as given in Table 1 and $\alpha/2$ = 2. The intervals would slightly overlap and we would not expect to find a significant difference between the means; or, we would not be able to state from our data that a change has occurred. Employing the paired random method, with $\sigma_{\bar{d}}$ from Table 9 and a $\bar{d}$ of 2.1, we find we would need only 43 samples to achieve significance. As predicted by statistical theory, efficiency is gained using paired random tests. Other advantages are that the populations do not need to be normally distributed and the variances do not need to be equal (Miller and Freund, 1965).

In actual practice, where populations are relatively large and unknown, an investigator using the paired difference method may determine an appropriate sample number using Equation 12. A few random differences may be obtained from the appropriate strata with the chosen square size and dot density. The required sample size, n, may be calculated from the variance, (s^2), of the trial samples once the desired half-width, (d), of the confidence interval and appropriate Student's value are chosen. The calculation is (Steel and Torrie, 1960:86)

$$n = t^2s^2/d^2. \tag{12}$$

Of course, the more trial samples taken the better the calculation of n will be.

We have applied the paired random sample differences technique to several areas in

TABLE 9. MIMINUM OBSERVED SAMPLE DIFFERENCE REQUIRED FOR SIGNIFICANCE (95 PERCENT CONFIDENCE) AND $\sigma_{\bar{d}}$ FOR EACH, PAIRED AND UNPAIRED RANDOM METHODS, 1974–1966

n	Hay		Cultural Features	
	% area			
	$\bar{d}$			
	Paired	Unpaired	Paired	Unpaired
26	6.8	10.6	2.8	4.0
32	6.0	9.4	2.4	3.4
43	5.0	7.8	2.0	2.8
65	3.4	5.4	1.4	2.0
	$\sigma_{\bar{d}}$			
26	3.4	5.3	1.4	2.0
32	3.0	4.7	1.2	1.7
43	2.5	3.9	1.0	1.4
65	1.7	2.7	0.7	1.0

Whatcom County and reported that pasture land decreased significantly on non-prime lands county wide; forest land decreased while row crops and cultural features increased on prime lands of the Guide Meridian area (consistent with the means in Table 1); and hay increased, apparently at the expense of pasture, in two adjoining areas (Frazier and Shovic, 1979).

Summary and Conclusions

The complexity of populations measured by variance and skewness, varies with category of land use, date, scale of photography, and kind of stratification. Different sets of land-use categories, sample area, or dot density may also change the numerical value of these parameters. Although these limitations exist, which reduce direct application of our work to other studies, within one study the parameters can be estimated and used for measures of precision and sampling method decisions.

Trials with variable sample square areas and dot densities indicate that either 2.6 km^2 samples with 8 dots/km^2 or 1.26 km^2 samples with 15 d/km^2 will give similar means and acceptable standard deviations. Smaller standard deviations are possible but only with greatly increased effort, approximately doubling the number of dots counted.

Area-point sample distribution by random or stratified random procedures showed no large differences in efficiency for the strata used in this study. Systematic distribution has the potential of producing varying precision of results due to linear or periodic landscape features. In all cases, paired random samples are more efficient than unpaired samples in showing differences between two dates.

Error estimates for random placement of a systematic grid over the entire area may be studied by Bonnor's technique or estimated by repeated trials. Obviously, if large areas are to be covered, the systematic canvass becomes either too costly or accuracy is reduced. Using random error calculation formulae for systematic methods should be avoided since land-use distributions may be influenced by landscape features and, thus, are not randomly distributed. Systematic sampling methods may be successful with randomly distributed populations, but the statistical literature and our own experiment does not support their use on other populations. The alternative is to randomly sample less than the total area with sample squares with dot densities determined to minimize the coefficient of variation and the labor involved.

Any study should have some formal error estimation to determine the reality of observed differences with a given sample size. Then, reported results will be meaningful for comparison to other studies and real changes can be separated from those resulting from random error.

The decision regarding required precision and, therefore, study intensity, must be made by those using the data. We need to ask ourselves whether the data really represent the landscape with which we are trying to deal. The ratio of the total sample area to the population area is not seen as a significant justification of precision, since up to 49 percent of the area in this study was sampled with significant error still present. Obviously, there are other factors involved in addition to sample proportion.

It is believed that, with proper selection of sampling methods, statistical theory and error estimation can be applied to land-use determination. The important parameters to determine are (1) sample square size sufficient to portray landscape complexity, (2) adequate number of samples, and (3) the type of random method to apply. If the first requirement is met and the allowable error and random method set, the number of samples may be determined in the usual manner.

In our opinion, if we are to plan for changing uses of agricultural land, planners have to know what is coming and where before it arrives en masse. It does little good to know where the subdivisions are after they are built unless we are interested in historical changes. We need to be able to measure the subtle changes rapidly and with some measure of precision before the massive building starts.

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