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Population Estimates by Humans and Machines

Results of significance tests of the variation of human interpretation of urvan built-up areas show the need for machine interpretations to minimize perception variations among human interpreters.

Abstract: *A comparison of population estimates of small urban settlements derived from aerial photographs by human and machine interpretation indicates that the accuracy at any given central place has not been significantly improved over that of delimiting built-up areas with image interpreters. An Image Discrimination, Enhancement and Combination System (IDECS), a system designed for image enhancement and information processing, was developed for interpreting and measuring the size of urban areas from which population estimates can be computed quickly, and a computer program was prepared for the purpose. Regression studies indicate the accuracies of several examples based on black-and-white aerial photographs. Machine interpretation offers savings in time over human interpretation. The small errors in obtaining total population with either human or machine procedure demonstrates that the relationship existing between population of urban places and their respective urban areas could be useful to governments of all nations.*

Introduction

Geographers, demographers, and many others are interested in world population, its distribution and dynamics. The primary sources of data for population studies are national censuses and vital statistics. However, the accuracy and the completeness of these censuses varies considerably throughout the world and, even today, reliable censuses have not yet been made in some of the lesser developed areas of the world.[1] Some investigators[2,3,4] have suggested that aerial imagery may offer an alternative source for deriving population data in some of these areas for which data are very scant. Additionally, it has been expressed that aerial photography/radar imagery may be a useful source for deriving intercensus population estimates in those countries where censuses are now being made. Eyre[5], et al., in their population studies of Jamaica note further that aerial photography has potential for revealing inadequacies of censuses such as population existing but omitted in the census or population nonexistent but enumerated in the census.

A potential application of aerial imagery to population data collecting that has received some attention has been expressed through the use of the population-urban area relationship.[2,3,4,6] In particular, populations of urban places have been estimated from their built-up areas on the basis of the functional relationship that exists between the size of the population and the size of the settled area of the central places. Early formulations[7,8] of the relationship, however, were made for the purposes of deriving estimates of the built-up area of urban communities, for which data also are frequently not readily available, on the basis of the known populations of the urban places. Nordbeck,[8] for instance, derived population-urban area relationships for American, Japanese, and Swedish cities using the model $A = aP^b$ where A is the estimated area, P the known population, and a,b are computed constants.

Wellar,[3] using Nordbeck's formulation for American cities, inverted the analysis

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whereby population estimates of some Gulf Coast communities were made from measured built-up areas as viewed from Gemini space photography. However, he found the estimated populations of several cities differed considerably from the actual in using Nordbeck's model.[9] For instance, the population of Lake Charles, Louisiana, a city of 67,000 people in 1962, was underestimated by 29,500 people. On the other hand, Angleton, Texas, a small community with 7,312 people in 1962, was overestimated by only 488 people. Holz, et al.,[2] in another study conducted of the Tennessee Valley found that the population-urban area formulation, although slightly different than Nordbeck's, similarly resulted in considerable estimation errors of population settlement size. They found this particularly true for larger cities. These findings, as Wellar[3] suggests, would seem to indicate that further refinements are needed in the modeling/in interpretation procedures.

Factors of interpretation would seem to bear clearly on the problem of population-estimating accuracy using the above model. In the first place, it is difficult to determine precisely where urban land uses end and agricultural or other rural land uses begin. No doubt, because of this definitional vagueness, inclusion of land uses which have no functional relationship to the population of the central place could easily be made thereby causing considerable estimating errors to be incurred. Because of this problem, Sabol[4] in his work of population estimating of urban places on the basis of radar derived urban areas used a mean interpretation where an average was computed from several image interpreters measurements of a sample of urban communities in the United States. Although this seems to be a satisfactory procedure, considerable amount of time could be expended in obtaining these mean interpretations, particularly if one were attempting to acquire a complete data set for a densely populated country, and therefore the potential that this procedure seems to offer for acquiring rapid population estimates of urban centers would probably not be realized. Therefore, it would seem that other alternative interpretation procedures need to be developed and tested to further assess the appropriateness of population estimation of urban places from remote sensing imagery using the population-urban area relationship.

The purpose of this study is to demonstrate the applicability of automatic and semi-automatic interpretation procedures of the IDECS (Image Discrimination, Enhancement, and Combination System) that has been in continual development at the University of Kansas Center for Research, Inc., for interpreting and measuring the size of urban areas from which population estimates of urban places can quickly be computed. The IDECS is an analog-digital image processing system designed to perform a wide variety of enhancements, measurements, and category discriminations on single and multiple images.[10] Currently, the input images must be in photographic form, but the source may be aerial photography, airborne radar, infrared, multi-spectral scanner, medical or industrial *x*-rays or maps. Images are inputted by a scanner and may be outputted on a color display unit, on a black-and-white monitor, as area measurements on a counter, or on a pseudo three-dimensional display. In addition, a PDP-15/20 computer (Digital Equipment Corporation) has been interfaced to the system so that the IDECS can be program controlled and possess a wider capability in performing image enhancements and category identifications. Moreover, the PDP-15/20 will perform the task of calculating the statistics from data gathered by the IDECS.

For the problem at hand, single black-and-white vertical aerial photographs of 23 small settlements (ranging from 141 to 5,010 people) in eastern Kansas (see Figure 1), acquired from the Agricultural Stabilization and Conservation Service at an approximate scale of 1:20,000 for 1966, were used as the input to the IDECS. These images offered the most nearly uniform data set available from which to make area measurements. Human interpreters also used these photographs for delimiting the built-up areas of these same central places from which data comparisons could be made with those data sets generated from the IDECS and to document the magnitude of interpreter variations in interpreting the extent of settlement areas. Population data for the same year were obtained from documents prepared by the Kansas State Board of Agriculture.[11] Simple correlation and regression techniques were then applied to determine the population-urban area relationship in eastern Kansas and to derive estimating equations. Statistical tests of significance were used to document the variation in interpretations of built-up area among image interpreters and between estimated populations and the actual populations of the 23 settlements.

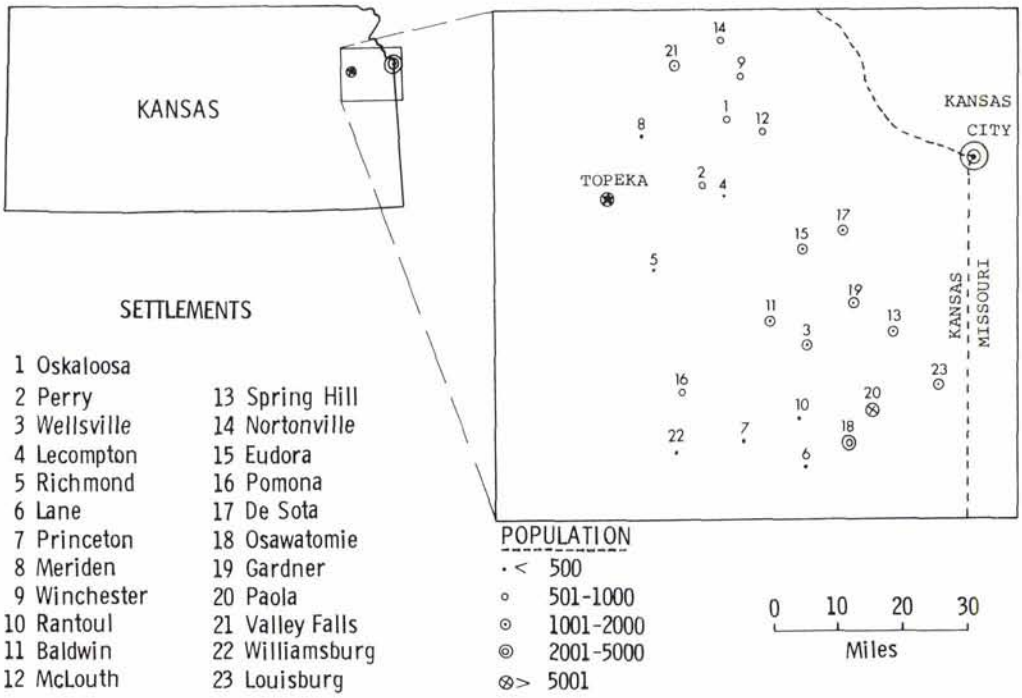

FIG. 1. Location of the study area.

URBAN AREA MEASUREMENT

Urban area measurements with the IDECS consisted essentially of three steps involving computer-assisted programming (see Appendix 1*). Upon entering the images on the scanner, dimensional data relative to image size were first inputted to the PDP computer to make proper scale conversions into ground distances. Next, the images were enhanced on command from the computer. Streets and roof-tops, which generally yield lighter-image tonal returns, were enhanced as these features seemed to provide good estimating parameters of settlement population. Finally, and upon enhancement by the operator, the PDP computer directed the IDECS to scan the enhanced image and print the square feet enhanced.

The delimitation procedure by which to acquire built-up area data for the 23 settlements on the basis of human interpretations is described in Appendix 2.* Essentially, this procedure consisted of directing five image interpreters to trace the urban areas from the photographs on the basis of a general description of the types of land uses, i.e., residential areas, parks, playgrounds, schools, etc., common to urban communities. The amount of settled area delimited by the interpreters for each town was calculated with a desk calculator-digitizer using an area-integration program.

* For reasons of brevity, the appendices are not included here. Interested readers can obtain them by writing to the authors.—*Editor.*

DISCUSSION OF RESULTS

CURVE FITTING

Data trends of the plots of population of the 23 eastern Kansas communities against their photographically derived areas tend to vary with the interpretation method used (see Figures 2 and 5). The model which best fits the IDECS data is a linear one. However, the fit of the data generated by the human interpreters is best approximated with the curvilinear model of the type used by Nordbeck and others. Table 1 is a summary of the correlation and regression calculations.

For the IDECS data, the correlation coefficient r is slightly improved (a change from 0.89 to 0.91) if the linear model is used. The plot of settlement population against the IDECS-measured data also supports this model choice in that a straight line results when graphed on arithmetic paper (see Figure 2). This departure in model fit from the typical curvilinear model is probably a func-

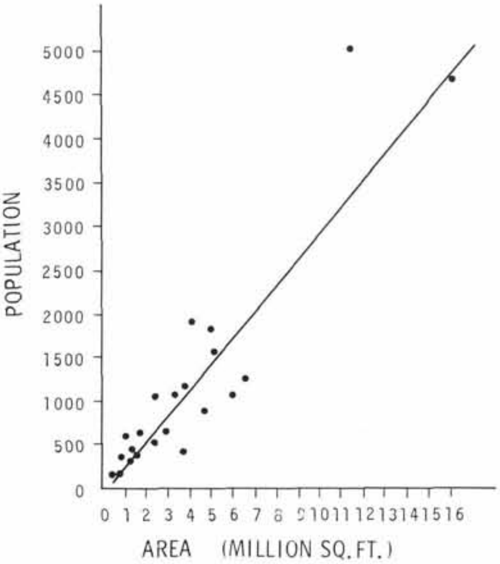

FIG. 2. Regression analysis of settlement population on IDECS-enhanced areas.

tion of the poor enhancement, largely due to streets and roof-tops being covered by tree tops in the older residential areas near the commercial districts where population densities are typically larger (see Figure 3). To verify, photographs of settlements with little or no tree cover should be processed on the IDECS to see if a similar functional relationship exists between the two variables.

The curvilinear model provides a better fit for the data derived from the human interpreters. In all cases, with the exception of one (interpreter Number 5), the r-values were improved upon using the non-linear model. Further, a straight line results if the population of the settlements are plotted against the average of the five interpreters measurements of built-up area on double logarithmic paper (see Figure 4). This is as would be expected for a relationship between two variables to be properly described by a growth model of the type discussed in the introduction. Figure 5 is the arithmetic plot of the data which shows a trend in a parabolic fashion, also indicative of this type of non-linear model. That the regression of population on human interpreted built-up areas yields the expected curvilinear relationship, and not the linear as found for the IDECS derived data, is likely explained by the fact that with this interpretation procedure the older, more densely populated sections of the towns are included and therefore reflect the changes in the proportion of area to population as settlement size becomes larger.

VARIATIONS IN INTERPRETATION

Using the regression equation for estimating purposes, the five interpretations of built-up area yielded highly variable results (see Table 2). A Kruskal-Wallis analysis, a non-parametric test, shows further that, indeed, a significant difference occurs in population estimation at the 0.05 level of significance on the basis of the five interpretations of built-up area (see Table 3). This generally supports the observations made earlier that the boundary, or even better described as a transition zone, between rural and urban land uses at the fringe of settlements is not likely to be drawn the same or perceived the same among image interpreters. Also, these findings are in agreement with Sabol's[4] choice of using an average of several interpreter's measurements. However, the derivation and calculation of an average for these data sets are quite time consuming. In

TABLE 1. CORRELATION AND REGRESSION RESULTS

Interpretation	*Linear Model* $y = a + bx$		*Curvilinear Model* $y = ax^b$	
	Correlation Coefficient (r)	*Regression Equation*	*Correlation Coefficient* (r)	*Regression Equation*
Machine				
Idecs	.91	$y = -79.06 + .0003\times$	.89	$y = .0004 \times^{.9819}$
Human				
Interpreter 1	.95	$y = -549.18 + .0002\times$	.95	$y = .000001 \times^{1.3085}$
Interpreter 2	.91	$y = -686.03 + .0002\times$	.95	$y = .0000001 \times^{1.4537}$
Interpreter 3	.93	$y = -439.79 + .0002\times$	.94	$y = .000002 \times^{1.2564}$
Interpreter 4	.93	$y = -544.51 + .0002\times$	.94	$y = .0000004 \times^{1.3412}$
Interpreter 5	.95	$y = -354.25 + .0002\times$	.92	$y = .000001 \times^{1.3144}$
Mean Interpretation	.94	$y = -591.54 + .0002\times$	.95	$y = .0000003 \times^{1.3631}$

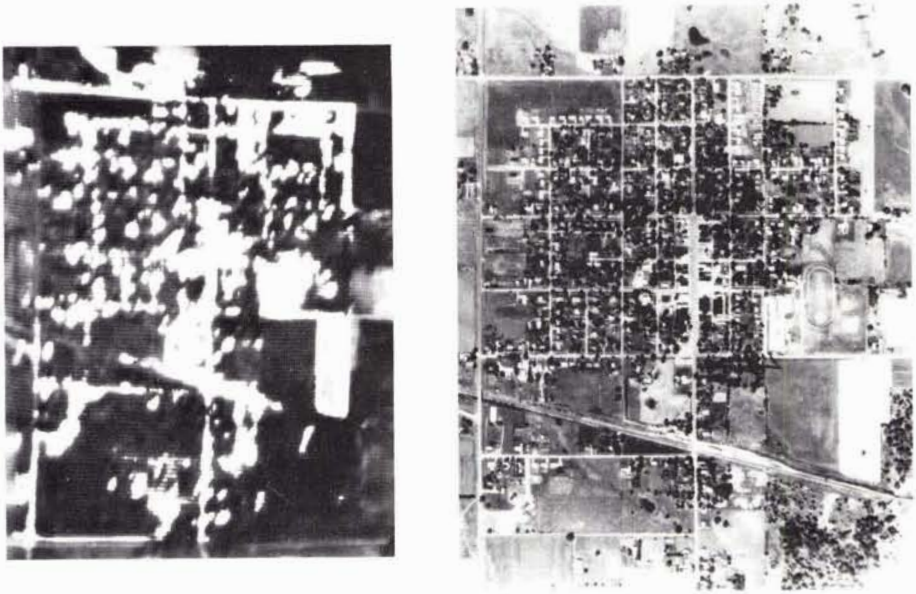

FIG. 3. IDECS urban area discrimination; IDECS enhanced area on left, photographic input on right.

this problem it took approximately 10 man-hours to acquire the area delimitations from the five interpreters to measure the built-up areas and to compute the average. With the IDECS (although at the present not a completely calibrated and repeatable system) it took four man-hours. With design modifications to make the system complete in an operational sense, one person should be able to process a similar size data set in 15 to 30 minutes.

Next, it was necessary to determine if the estimates from the regression equations based on both IDECS and human interpreted areas are significantly different from the published population figures. Mann-

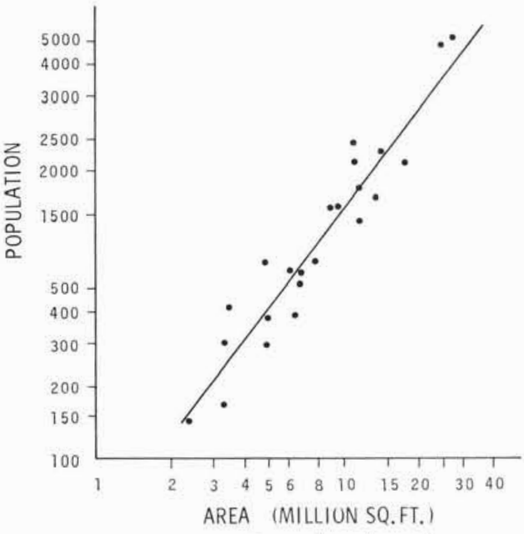

FIG. 4. Regression analysis of settlement population on mean-human-interpreted built-up areas (logarithmic plot).

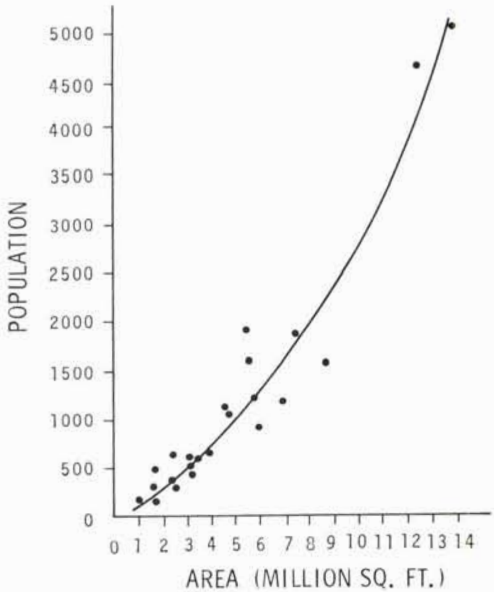

FIG. 5. Regression analysis of settlement population on mean-human-interpreted built-up areas (arithmetic plot).

TABLE 2. POPULATION ESTIMATES FROM REGRESSION EQUATIONS

Settlement	*Published Populations (1966)*	*Machine Interpretation*	*Human Interpretation*					
		Idecs	*1*	*2*	*3*	*4*	*5*	*Mean*
1. Oskaloosa	910	1,314	1,591	2,526	1,376	1,431	1,513	1,303
2. Perry	631	804	489	568	453	466	597	394
3. Wellsville	1,231	1,856	1,455	2,123	1,223	1,648	1,617	1,263
4. Lecompton	420	323	260	401	337	326	257	243
5. Richmond	399	1,001	698	956	711	562	700	556
6. Lane	299	295	249	372	297	260	362	233
7. Princeton	169	181	228	401	316	227	442	239
8. Meriden	373	397	468	552	444	465	648	399
9. Winchester	524	613	725	957	649	542	1,009	586
10. Rantoul	141	71	218	197	152	152	322	152
11. Baldwin	1,551	1,470	2,399	3,668	2,700	2,284	3,093	2,228
12. McLouth	572	212	698	863	578	549	916	546
13. Spring Hill	1,063	883	1,099	1,601	956	920	1,490	925
14. Nortonville	633	447	848	1,127	756	678	1,310	714
15. Eudora	1,917	1,121	1,665	1,505	1,328	878	1,009	1,135
16. Pomona	578	1,080	649	766	872	636	939	598
17. Desota	1,587	1,140	1,241	1,980	1,122	1,401	1,991	1,194
18. Osawatomie	4,677	4,713	4,082	5,385	3,824	4,003	5,497	3,638
19. Gardner	1,833	1,376	1,842	2,552	2,223	1,909	2,612	1,762
20. Paola	5,010	3,004	4,908	5,665	4,629	4,086	6,507	4,129
21. Valley Falls	1,171	1,037	1,119	2,254	1,976	1,816	2,368	1,582
22. Williamsburg	295	163	429	478	326	502	968	403
23. Louisburg	1,058	615	1,120	1,333	1,113	874	1,728	944
Total	27,042	24,116	28,480	38,230	28,361	26,615	38,884	25,166
% Error		10.8	5.3	41.4	4.9	1.6	44.0	6.9

TABLE 3. RESULTS OF SIGNIFICANCE TESTS

Test of Interpretation Variation Between	x^2 *— Value*°	z *— Value*°°	H_o	H_1
Kruskal-Wallis				
Human Interpreters	10.4		R	A
Mann-Whitney				
Idecs and Actual		.27	A	R
Interpreter No. 1 and Actual		.12	A	R
Interpreter No. 2 and Actual		1.66	R	A
Interpreter No. 3 and Actual		.71	A	R
Interpreter No. 4 and Actual		.03	A	R
Interpreter No. 5 and Actual		1.72	R	A
Mean Interpretation and Actual		.58	A	R

° Critical Value of $X^2_{.05} = 9.49$
°° Critical Value of $Z_{.05} = 1.64$
R - Reject
A - Accept

Whitney signifance tests, also a non-parametric statistic, were applied to determine the two-way differences between estimates and the actual populations of the 23 settlements. These analyses show that the estimates based on the IDECS-derived areas and the mean-human interpretation of built-up area were not significantly different from the published data as was also the case for interpretations for interpreters Number 1, 3, and 4 (see Table 3). However, estimates based on interpretations 2 and 5 were found to be significantly different from the actual population at the 0.05 level of significance. It would seem in light of these results that a close examination of the way in which the delimited areas were perceived by those interpretations that were not significantly different from the actual populations could be helpful for writing future interpretation procedures. In this way it may be possible to direct human interpretations such that consistent results can be acquired from image interpreters.

The variation in interpretation is further reflected by the per cent error incurred in estimating the total population (the sum total) of all 23 settlements. For instance, the range in magnitude of error among human interpreters is from 1.6 per cent to 44.0 percent, whereas the average for the five interpretations errors by about 7.0 percent. With the IDECS the error was 10.8 percent. Errors in estimating a given urban place were found to be of similar magnitudes experienced by other researchers reported on earlier in the paper, regardless of interpretation procedure used. The settlement of Wellsville, for instance, with a population of 1231 people in 1966 was overestimated by the IDECS result by 51 percent and by the mean human interpretation result by only 3 percent. On the other hand, Baldwin, with 1,551 people, was estimated within 5 percent of its actual size with the IDECS calculations while the average interpretation resulted in a 44 percent error.

These estimating errors of individual settlements, no doubt, still reflect interpretation problems. As mentioned, the IDECS discrimination in older residential sections was difficult due to tree cover. Also, on the fringes of the settlements agricultural fields with similar tonal returns as many of the streets and roof-tops became bothersome at times during enhancement (refer back to Figure 3). In some instances, more area was included than would have been liked and in other instances there was less area included than desired. Therefore, the nature of these interpretation errors, both undermeasurement and over-measurement, for a large data set has a canceling affect.

Summary

On the basis of the above analysis, it appears that the IDECS area enhancement and integration routine offers a potentially useful automatic interpretation procedure from which to obtain quick urban population estimates on the basis of their urban areas. However, the accuracy with which any given central place can be estimated has not been significantly improved over that of delimiting built-up areas with image interpreters. The results of the significance tests of human-interpretation variation of urban built-up area, however, show the need for machine interpretations which will assist in minimizing perception variation among image interpreters. Also, the savings in time that machine interpretation offers over acquiring averages for areas interpreted by human interpreters seems to merit further attention. The small estimating errors for obtaining the total population of all settlements with either interpretation procedure demonstrates that the relationship existing between population of urban places and their respective urban areas could be useful to governments of all nations for obtaining estimates of urban population by areal units (i.e., counties, states, districts, etc). Combining the population-urban area procedure with counts of rural dwellings on the basis of an average sized family would further allow estimates of the total population residing by areal units and facilitate categorizing population data by rural and by urban, as typically done during census enumerations.

Recommendations for Future Research

Future experimentation needs to be done to determine if other types of urban areas representative of urban population size, such as commercial districts, with more precise-delimitable boundaries, are more interpretable from both the machine and the human interpretation points of view. A preliminary experiment indicates that this is possible. The commercial districts of these same 23 settlements were measured and correlation and regression analysis was performed to determine the nature of the relationship between population and these commercial areas. A linear relationship with an *r*-value of 0.93 best described the relationship (see Figure 6); and, therefore, seems to give further support for studying in

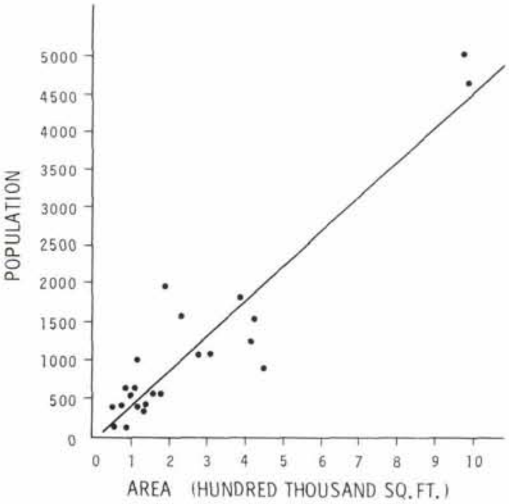

FIG. 6. Regression analysis of settlement population on delimited commercial areas.

more detail this procedure for acquiring estimates. Also, this procedure should reduce significantly the time needed to make area interpretations and to calculate the respective areas. This would be particularly significant for measuring large cities where a number of photographs at aircraft scales would have to be used to acquire the total view of the urban area. By limiting the interpretation area to the smallest features, yet still proportional to the population, time required for procuring the imagery and organizing it should be markedly reduced. This observation, of course, has to be qualified with regard to spacecraft images of scales of such small size that whole metropolitan areas can be viewed on one or two frames.

Further testing of model variations based on human interpretation and IDECS machine enhancements of variable types of urban areas with larger samples and larger settlement size ranges would also seem fruitful. For instance, it would be useful to know within what range of population settlement size the linear model holds for interpretations of selected urban features. This should help the researcher and potential user make the appropriate model selection. Also, and as others[2] have suggested, there is a need to know how frequently the model(s) have to be calibrated in population growth regions versus areas of population stagnation and decline. Measurement of differential growth of urban places from aerial imagery might also be considered.

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Articles for Next Month

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