A Raster Approach to Population Estimation Using High-Altitude Aerial and Space Photographs

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Introduction

The use of large-scale aerial photographs for population estimation employing the dwelling unit count method has been capable of producing population estimates at the census tract level with an accuracy (in terms of relative error) of about +0.90 percent (Lo, 1986). According to Watkins (1984) and Watkins and Morrow-Jones (1985), the accuracy of population estimation depended on the occurrence of multi-unit structures which made the counting of dwelling units difficult. In addition, the accuracy of the household size and vacancy rate figures which have to be employed to compute the population size from the number of dwelling units counted could also affect the ultimate accuracy of the population estimates. Despite these difficulties, it is generally agreed that the photographically derived dwelling unit count method of population estimation using large-scale (say, 1:10,000) aerial photographs can produce fairly accurate results at the census tract level.

One major handicap of this method of population estimation is the time-consuming process of dwelling unit count which normally is conducted with the aid of a mirror stereoscope and magnified binoculars. Another problem is the large number of aerial photographs that have to be used to cover one whole city. In moving from one photograph to another, care has to be taken to avoid omission or commission in identifying and counting the dwelling units. Thus, the main objective of this research was to find a new approach which could ease the tedious nature of dwelling unit count method of population estimation while still maintaining the level of accuracy specified above. Another objective was to evaluate such an approach on the basis of high-altitude aerial photographs and space photographs which provide a better synoptic view of the city area. Finally, the incorporation of population estimation into a Geographic Information System (GIS) was also explored.

The Raster Approach to Dwelling Unit Determination

In order to simplify the procedure of dwelling unit count, one possible approach is to determine the residential building density in different parts of the photograph. This is equivalent to determining the tonal density of the photograph, which should be directly correlated with building density. An accurate way of doing this is to divide the aerial photograph into a number of small regular-sized grid cells. The size of the grid cell is determined by the spatial resolution of the aerial photograph being used. Such a procedure, therefore, converts the photographic data into a raster format which can be easily accommodated by the computer.

The determination of building density in each grid cell was facilitated by referring to a transparent sheet of 10 mm x 10 mm dot grid over each grid cell. The theoretical maximum number of dwelling units that could occupy the whole grid cell at the ground level was first determined. The percentage of dwelling units actually occurring in each grid cell was then estimated from the aerial photograph. By multiplying the actual percentage to the theoretical number, the actual number of dwelling units in that grid cell was obtained. This process was complicated by the fact that dwelling units could occur at different levels in multistoried buildings. In such a case, the use of a mirror stereoscope and the stereoscopic aerial photographs allowed the number of stories of the buildings to be estimated with reference to single-storied structures in the environs. Multiplying the number of stories to the theoretical maximum number of dwelling units at the ground level provided a new basis for computing the actual number of dwelling units in these multistoried structures after the actual percentage had been estimated.

In order that only residential building densities were determined, the whole process was preceded by an interpretation of the use of individual buildings. Basically, a dichotomous classification into residential and non-residential is sufficient for the present purpose. However, a broad Level I land use classification of each grid cell was carried out. In such a case, only the dominant land use in each grid cell was recorded.

This new approach to dwelling unit count was also applied to the Large Format Camera (LFC) photographs, of the same study area acquired from the Space Shuttle Mission STS-41G on 5 October 1984 (Doyle, 1985). The LFC photography exhibited excellent spatial resolution and geometric accuracy (Derenyi and Newton 1987; Lo, 1988). Despite such excellent spatial resolution, individual buildings were not always distinguishable even after 15.6 times of enlargement. The method of dwelling unit count explained above can be easily modified into one which estimates only building densities on a grid cell by grid cell basis. This idea is borrowed from the foresters' use of crown density scale to determine the percent of crown closure from aerial photographs (Moessner, 1947). If we can establish the theoretical maximum number of dwelling units for each grid cell, based on the ground truth established by the high-altitude aerial photographs, the number of dwelling units in each cell should be determinable from the building density extracted from the space photograph.

Results of Application

The approach described above was applied to estimate the population of Providence, Rhode Island using 1:80,000 scale black-and-white National High Altitude photography (NHAP) and Large Format Camera photography enlarged to a scale of 1:50,000 from its original 1:756,000 scale.

(A) Use of National High Altitude Photography (NHAP)

The NHAP of Providence which was acquired on March 16, 1985 is of excellent quality. The grid-cell size employed was 0.5 x 0.5 cm which is equivalent to an area of 0.4 x 0.4 km or 0.16 km^2. This size was found to be the smallest acceptable for visual interpretation and should not result in too many grid-cells as to hamper handling ease. On the high altitude photograph, an average dwelling unit was recorded in a size of about 0.2 x 0.2 mm. By putting a transparent grid of 0.5 x 0.5 cm over the normal single-storied residential structures on the high altitude photograph, one could easily determine the maximum number of dwelling units at ground level per grid cell to be 375 which provided the theoretical basis for visually determining the actual percentage of dwelling units in each grid cell. All together 96,048 dwelling units were counted in this way. There were 1,086 grids with building structures. The mean number of dwelling units per grid cell was 88.4 and the mean building density was 552.7 building units per km^2. The highest number of building units per cell was 788, thus giving the highest building density of 4925 building units per km^2.

These building data by grid cells had to be aggregated into appropriate census tracts based on the census tract map of the 1980 census (Bureau of the Census, 1983). Because of the irregular-shaped census tract boundaries, the grid data could only be approximately fitted. At the border between two census tracts, it was necessary to assign the building data in one whole grid cell to the census tract which occupied more than half of the area of the grid cell. There were all together 92 census tracts in the study area. It is hoped that this number is large enough to compensate for the over- and under-assignment of grid cell values at the census tract boundaries.

These building unit data by census tracts were compared with the housing unit data obtained by the 1980 census (Bureau of the Census 1983). It became evident that the photography-derived building unit data grossly underestimated the actual number of housing units. This was not surprising in view of the fact that the number of building units was estimated based on the percentage of a theoretical maximum. However, it was found that by taking the common logarithms of both the actual number of housing units and the photograph-derived number of building units, the two variables gave rise to a highly significant correlation of 0.742 and a double-log model in the form of:

$$\log (NOHU) = 1.6454 + 0.5415 (\log NOBG)$$

where NOHU is the number of housing units and NOBG is the number of building units obtained from aerial photographs. Thus, by applying this model it was possible to obtain the corrected number of dwelling units that provided the basis for population estimation. Comparing these corrected dwelling unit data with the 1980 census data on the number of housing units by census tracts gave a mean relative error of 4.26 percent.

The next question was: what would be the appropriate household size value to be used for calculating the population from these dwelling units?

By analyzing the 1980 Census data for the city of Providence, it was possible to compute the average number of persons per dwelling unit by census tracts. When these residential population densities were mapped, it became obvious that seven distinct categories of data on the number of persons per dwelling unit emerged from the map. The mid-point value of the appropriate category of data for each census tract was employed to compute the population size from the corrected estimates of dwelling units of each census tract. The predominant values were 2.3 and 2.6 persons per dwelling unit. This approach may be regarded as using regional estimates of population size per dwelling unit to compute population estimates. Finally, one could also obtain an overall population size per dwelling unit for the whole study area, irrespective of the regional variations. This figure was found to be 2.46.

In order to examine the effect of these two different approaches, namely, regional population density and overall population density, on the accuracy of population estimation, each set of figures was multiplied by the corrected number of housing units obtained from the double-log model at census tract level. Comparison was made with the estimated 1984 population figures for Providence obtained from the Bureau of the Census (1986). It was found that the resultant mean relative errors for using regional population densities and overall (average) population density were respectively +2.50 and +6.94 percent. As expected, the use of an overall population density gave a poorer result. The use of regional densities seemed to better compensate for the over- and under-estimation of population. If we examine the population estimates for each census tract obtained by the regional densities method, the relative errors were found to vary from a maximum of +97.7 percent to a minimum of +0.34 percent. Spatially, the inner city area suffered from an underestimation of population while the more outlying city area displayed an overestimation. This result clearly reflected the problem of multistoried structures and the mixing of residential and non-residential structures in the inner city area. Therefore, on the census tract basis, this method of population estimation is less reliable than the conventional dwelling unit count approach using large-scale aerial photographs, but its potential for the whole procedure being incorporated into a computer-based GIS is great.

(B) Use of Large Format Camera (LFC) Photography

The next stage of research was to apply the same philosophy of population estimation to space photographs. Only building densities as exhibited by the tone of the photograph were estimated on a grid cell by grid cell basis. This is particularly appropriate as the spatial resolution of the space photographs is much lower than that of the high-altitude arerial photographs. The LFC photographs of the Providence study area were obtained (frames 663 and 666). The two frames selected provided a base-height ratio of 0.90 which allowed an increased vertical exaggeration of the stereomodel to be obtained when viewed through a mirror stereoscope. The Providence area occupied only a small portion of the 23 x 46 cm LFC photograph. At its original scale of 1:756,000, it is too small for detailed population estimation by census tracts. The LFC photograph was therefore enlarged 15.6 times to a scale of 1:50,000. A stereomodel could be obtained with the aid of a mirror stereoscope. A transparent grid was laid on top of one photograph and the grid cell size employed was 1 x 1 cm or 0.25 km^2 at the photograph scale. These grid cells were placed in such a way that they corresponded as best as possible with the way the grid cells were laid out in the NHAP application. In this way, one could make comparison with the NHAP photograph to determine how much detail was lost in the space photograph. It was impressive to discover the excellent spatial resolution of the LFC photograph which compared favorably with the national high altitude photography used before. The percentage of residential buildings occupying each grid cell was visually determined with reference to a dot grid with a density of 100 points per cm^2. To obtain the theoretical number of dwelling units per grid cell, one first computed the mean percentage of residential buildings so determined from the LFC photographs on a per square kilometer basis. Since the mean density of dwelling units per sq. km. was known from the 1980 census, the mean number of residential buildings per sq. km. was obtained by dividing the mean density of dwelling units from the census by the mean percentage of residential buildings from the LFC photographs. The result was 1,382 dwelling units per sq. km. or 346 dwelling units per 0.25 km^2 grid size. The latter figure was multiplied by the percentage of residential buildings determined from the LFC for each grid cell to obtain the actual number of dwelling units. The overall relative error of dwelling unit determination by this method was -6.47 per cent. In order to obtain a population estimate for each census tract, both the overall household size and regional household size were employed as multipliers to the number of dwelling units per census tract. The overall household size method (2.32 persons per household) gave a mean relative error of -13.64

percent while the regional household size method gave a mean relative error of -8.24 percent, thus once again confirming the superiority of the regional household size in population estimation. One should note, however, that the use of LFC photographs gave much inferior results of population estimation to those for NHAP photographs. The underestimation of population in the case of the LFC photographs was obvious and could be explained by the difficulty in dealing with multistoried buildings in the process of determining the percentage of residential buildings in each grid cell.

The GIS Approach to Population Estimation

The raster approach to dwelling unit count provided a convenient data format for storage by the microcomputer. In order to explore how such a new approach could be incorporated into a GIS, the dwelling unit data obtained from NHAP photographs of Providence were entered into a Zenith Z-159 personal computer with the PC-Write program. The PMAP GIS package (Berry and Reed, 1987) was employed in the analysis. Three other sets of data, namely, census tract boundaries, land use, and household size by census tract were also entered into the computer. The program permitted easy display of all these four sets of data as choropleth maps (Figs. 1, 2 and 3). From the land use map, the residential use could be singled out (Fig. 4) which was then combined with dwelling unit map to produce a residential-dwelling unit map (Fig. 5). By combining household size with residential-dwelling units, one could obtain population estimates for each grid cell and for aggregation into census tracts. To do the latter, one had to identify individual census tracts using the census tract map and the residential-dwelling unit map. A data file of population estimates for any census tract could be generated and copied into a data diskette where further analysis of the population data, using the PC-SAS package could be carried out (Fig. 6). One major advantage of this GIS approach to population estimation was the flexibility with which household size data could be updated or changed.

Conclusions

This paper investigated the usefulness of the raster approach and the crown closure determination method to population estimation using high altitude aerial photography (NHAP) and space photography (LFC). Such an approach has the advantage of simplifying the time-consuming procedure of the conventional dwelling unit count method using large scale aerial photography. The underlying principle of this approach is the discrimination of residential building coverage by tonal changes. The determination of a theoretical maximum number of dwelling unit per grid cell provided a means to relate the tonal data with the dwelling unit data. If proved successful, the whole process can be automated with the aid of a scanning densitometer and a microcomputer. The use of a raster format allows the dwelling unit data to be incorporated, along with land use, census tract, and household size data, into a microcomputer-based Geographic Information System (GIS). The commercially available PMAP package for microcomputer has been found to be capable of producing population estimates by census tracts and maps with ease.

The major concern of this study, however, lies in the accuracy of the new dwelling unit count and population estimation approach, which was found to be not as good as the conventional approach using low-altitude aerial photography. In the case of application to NHAP, individual buildings could still be seen and their functions interpretable in each grid cell.

Even the number of stories of the building was visible. However, underestimation of the actual number of dwelling units inevitably occurred. Fortunately, this could be corrected by the application of a double-log regression model, calibrated with reference to existing census data. The resultant accuracy of population estimation by census tracts varied from +2.50 to +6.94 percent (relative error) depending on whether regional or mean household size was used in the computation.

The application to LFC photography was found to be feasible in generating population estimates. However, in view of the lower spatial resolution of the LFC photography compared with NHAP, individual buildings could no longer be seen. Tone was the sole image element for determining the extent of occurrence of residential building cover in each grid cell. Although stereoscopic viewing of the LFC photographs (already enlarged 15.6 times) was still possible, the presence of multistoried structures posed some difficulty in accurate estimation of dwelling units. The resultant accuracy for population estimation varied from -13.64 per cent with the use of mean household size in the computation to -8.24 per cent with the use of regional household size in the computation. The root mean square errors (RMSE) of the estimates were also computed for each case, and it was found that there were larger RMSE for this method applied to LFC photography than that applied to NHAP photography, thus suggesting that the precision of the population estimates derived from LFC photography was poorer than that for NHAP photography. The implication clearly is that while it is possible to obtain fairly accurate population estimates for a region by the new approach, the sub-regional population estimates tend to fluctuate greatly. A possible refinement approach at sub-regional level is to develop one or more mathematical models which will correct for undercounting of dwelling units based on tonal variations. For this to be successful, good quality ground truth data on population will be required. It is simply impossible to improve the method based on outdated population and housing statistics from the Census Bureau.

Despite the mediocre results in population estimation, this research has demonstrated the great potential of high-altitude aerial photographs and space photographs to quickly obtain dwelling unit data in raster format as input to a GIS. The GIS approach has been shown to exhibit a high degree of flexibility which permits mapping of population distribution and updating of population estimates on a regular basis for a city area. All this should prove to be an invaluable tool to the planners.

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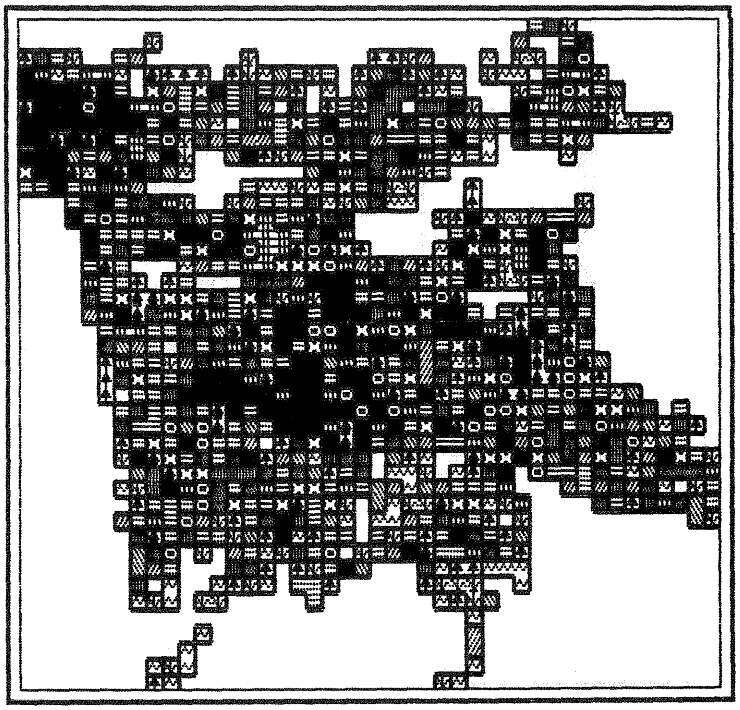
List of Illustrations

FIG. 1

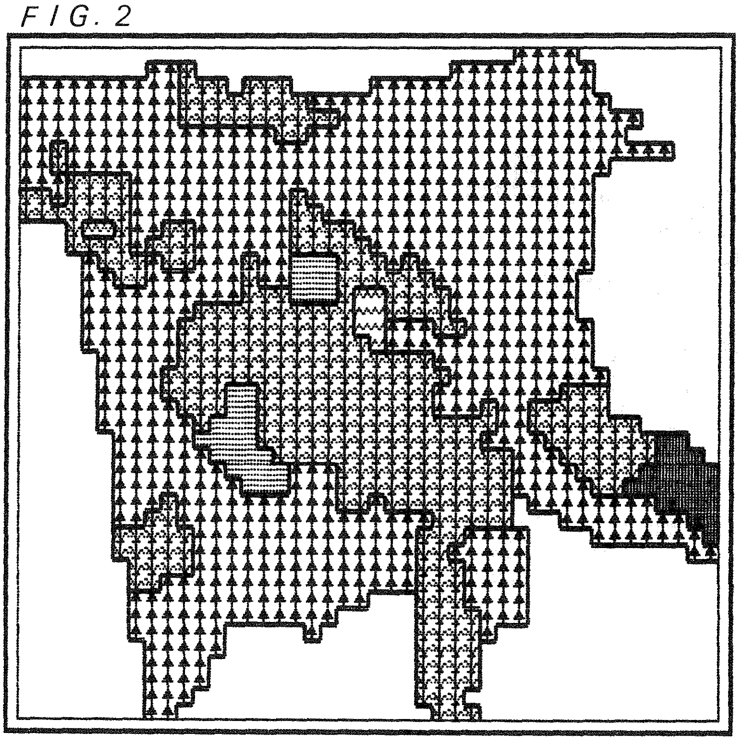


SYMBOL	VALUE
	0
(wavy)	1
(stars)	2
(arrows)	3
(horizontal lines)	4
(diagonal hatch)	5
(reverse diagonal hatch)	6
(dense shading)	7
(double lines)	8
(dark shading)	9
(boxes)	10
(cross-hatch)	11
(X boxes)	12
(circles)	13
(solid arrows)	14
(solid)	15

DWELLING.10
SCALE: .4 KM PER CELL

NO OF DWELLINGS IN 10'S

FIG. 2



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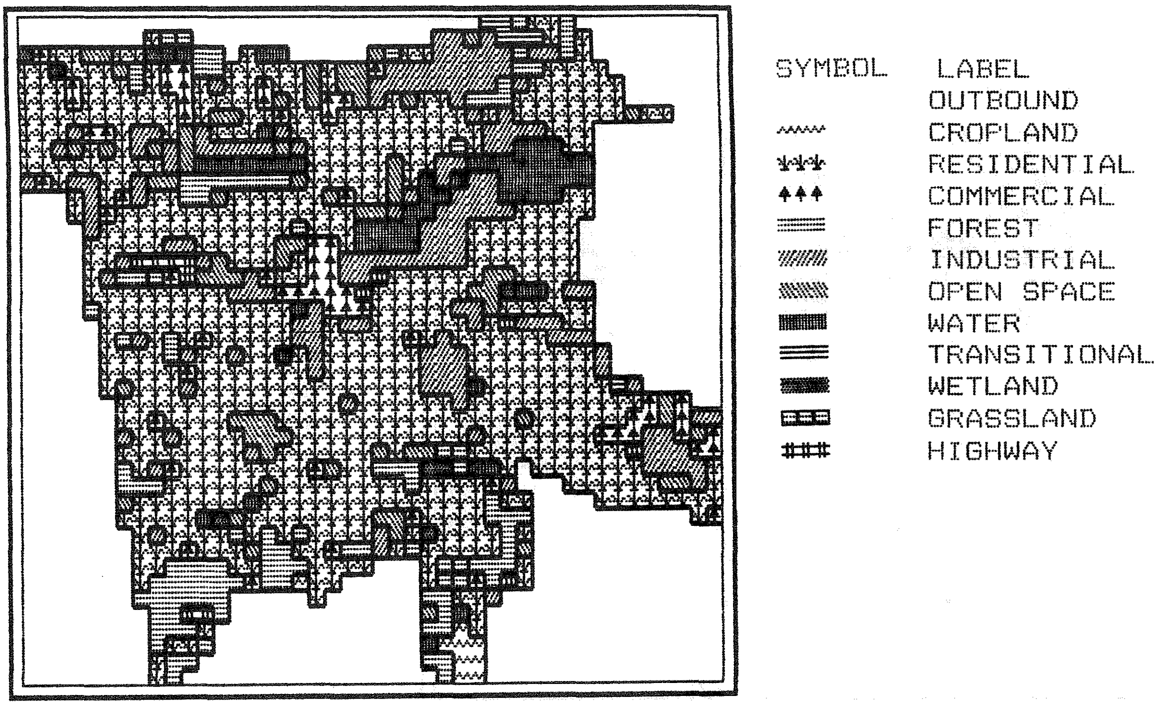
(arrows)	3
(horizontal lines)	4
(dense shading)	7

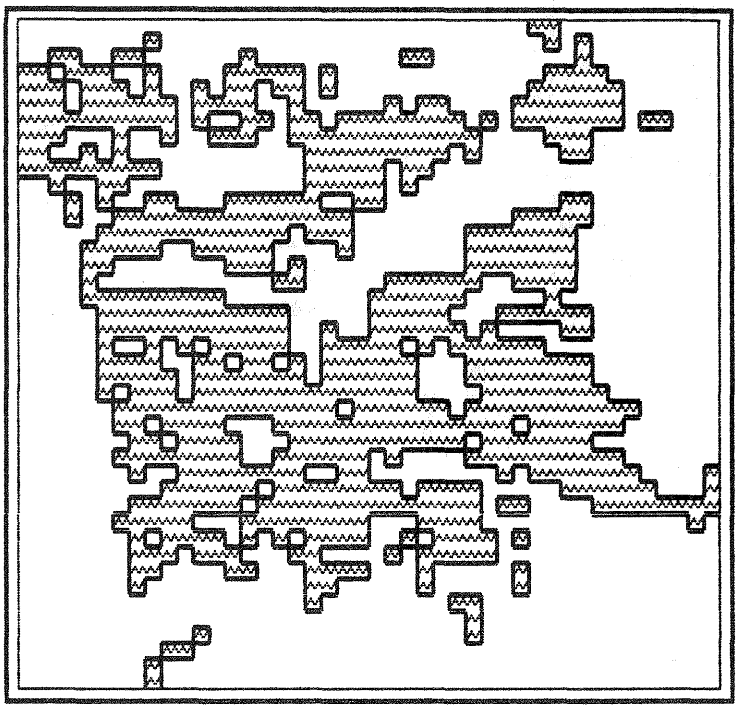
POPDEN
SCALE: .4 KM PER CELL

FIG. 3



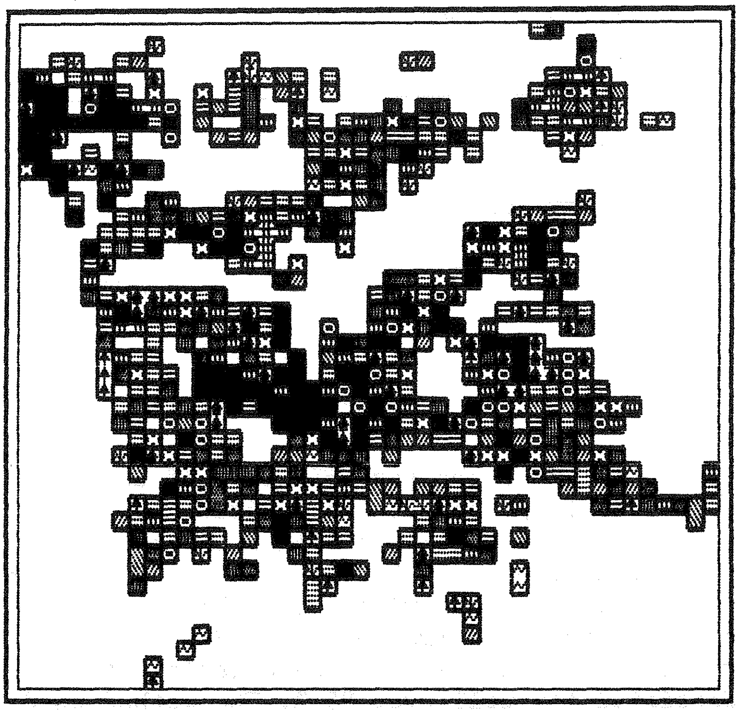
LANDCOVER
SCALE: .4 KM PER CELL

FIG. 4



RESIDENTIAL
SCALE: .4 KM PER CELL

FIG. 5



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[symbol]	11
[symbol]	12
[symbol]	13
[symbol]	14
[symbol]	15

RESID-DWELL
SCALE: .4 KM PER CELL

FIG. 6.

POINT FOR POPULATION OF CENSUS TRACT 16

9	23	140
10	23	260
6	24	110
8	24	300
9	24	320
10	24	230
7	25	120
8	25	210
9	25	250
10	25	310
11	25	220
7	26	230
8	26	240
10	26	410
11	26	200
8	27	300
9	27	360
7	28	70
8	28	450
9	28	440
10	28	360
8	29	200