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COMPUTER GRAPHIC PLOTTING AND MAPPING OF DATA IN SYSTEMATICS

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Summary

The use of the computer to map and/or plot systematic data is examined in the areas of automatic plotting of taxa's distributions and computer graphic analysis of geographic variation and population differentiation. Automatic plotting of distributional data is discussed in reference to earlier work and present applications in conjunction with the development of the Rapid Access Plant Information Center (RAPIC) of Colorado, (USA). In the area of computer graphic analysis of geographic variation, the following techniques are discussed: contour mapping (2 and 3 dimensional); shading by overprinting; contoured factor analysis; and contoured surface trend analysis. A technique of composite overlay mapping is introduced to systematics and several applications are discussed.

Why Map Data in Systematics?

There are at least three reasons why systematic data has been mapped. Perhaps foremost has been the mapping of collection sites in order to show generally where a particular taxon has been collected. These maps are useful in determining where to do additional collecting and deducing general distributional patterns of taxa. Valuable field time is saved by plotting herbarum voucher locations. Secondly, the mapping of distributional data enables one to find out (at least partially) if taxa are sympatric, allopatric, or allopatrically sympatric. Areas of overlap can be ascertained to aid in the planning of studies of hybridization, introgression, gene flow hypothesis, etc. Thirdly, data are mapped to examine the correlation of a taxon's distribution with geography, climatic factors, edaphic factors, etc. These studies on the infraspecific level are often concerned with explaining patterns of population differentiation respect to geography and thus mapping becomes a primary tool. The purpose of this paper is to review the general field, broadly, with different examples, and discuss mapping from various vantage points. It is not to be considered a catalogue of the many computerized mapping projects around the world but a (hopefully) representative sample.

Early Mapping Efforts

Most of the early mapping efforts have been primarily concerned with determining where a taxon occurred and/or how the distributions of taxa compare. Maps consist of dot maps, shaded maps, stippled maps, etc., as commonly seen in Taxon. Recent more comprehensive hand mapping efforts have been accomplished by Faegri (1960), Hulten (1958, 1962), Little (1971) and others.

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Computer Mapping and graphic Plotting

At present it seems that the use of the computer to map and/or plot systematic data has been primarily in two directions: Automatic plotting of taxa's distributions; and computer graphic analysis of geographic variation and population differentiation. Since these two directions of study are somewhat divergent, they will be treated in separate sections.

Automatic Plotting of distributional Data

Perhaps the earliest work in this area was by Perring and Walters (1962) on the *Atlas of the British Flora*. Figure 1 shows a distribution map of *Rosa arvensis* Huds. from the *Atlas of the British Flora*. The shaded circles were printed on a line printer (tabulator) by running a series of computer cards through the printer. The open circles and xes were placed by hand to represent, in this case, records before 1930 and probable introductions, respectively. The datum was collected as presence/absence data in 10 kilometer grids throughout the British Isles. Considering the state of the art in automation in 1954 (actual beginning of their mapping), this project may well be considered a classic in this field. This project used a minimum of automatic

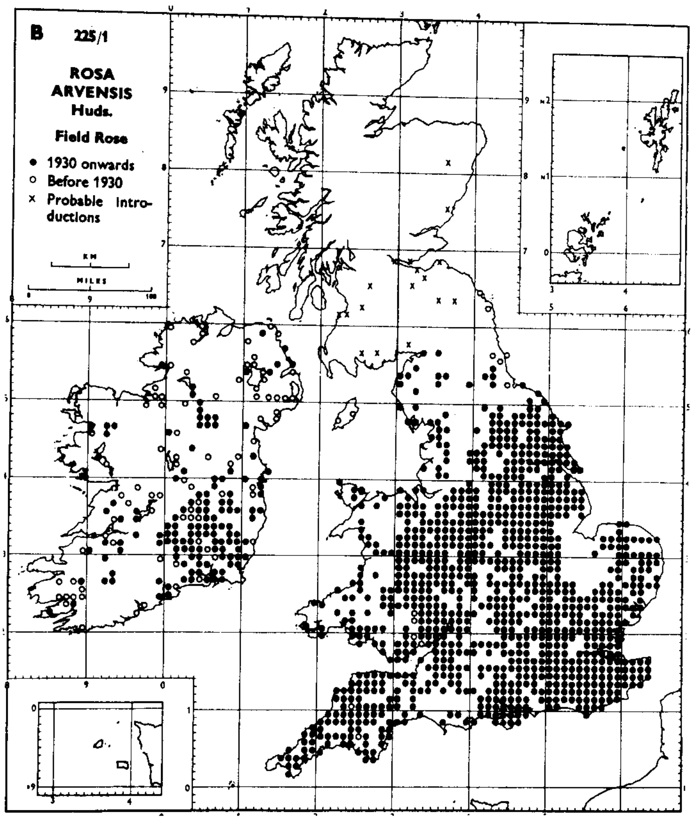

Fig. 1. Distribution records of *Rosa arvensis* generated by printing punched computer cards. Adapted from the *Atlas of the British Flora*.

equipment and an electronic digitial computer was not used nor needed. Only a card listing machine (line printer or tabulator), perhaps a card sorter, and a keypunch (to punch the cards initially) were needed. Various overlays such as average annual rainfall, altitude, geology, February minimum temperatures, etc., have been printed on clear plastic overlays which can be overlain on each distribution map to examine correlations.

Another early study is the work by Soper (1964, 1966) in conjuction with the Flora of Ontario Project. Several different plotting methods were examined by Soper ranging from tabulator systems to computer driven incremental plotters. Figure 2 shows a computer generated plot of southern Ontario, with locations of *Asplenium trichomanes* (adapted from Soper, 1966). This map was generated on a Calcomp plotter. Boundaries can be easily improved by additional points (see Soper, 1966, Figure 5 for a map with smoother boundaries). Some of Soper's work was first accomplished by printing onto base maps with a line printer but this was apparently discarded because of the spacing problems since the line spacing is not equal to the character width on line printers and on high speed printers the vertical spacing of characters is often not very uniform. Another problem associated with printing or plotting onto a base map is if the map is not positioned properly, all of the collection points will be misplotted. The plotting of the entire basemaps *de novo* eliminates this problem since all of the data, including the boundaries, are scaled by the computer before output (see Soper, 1966).

More recently, Cadbury, Hawkes, and Readett (1971) have published

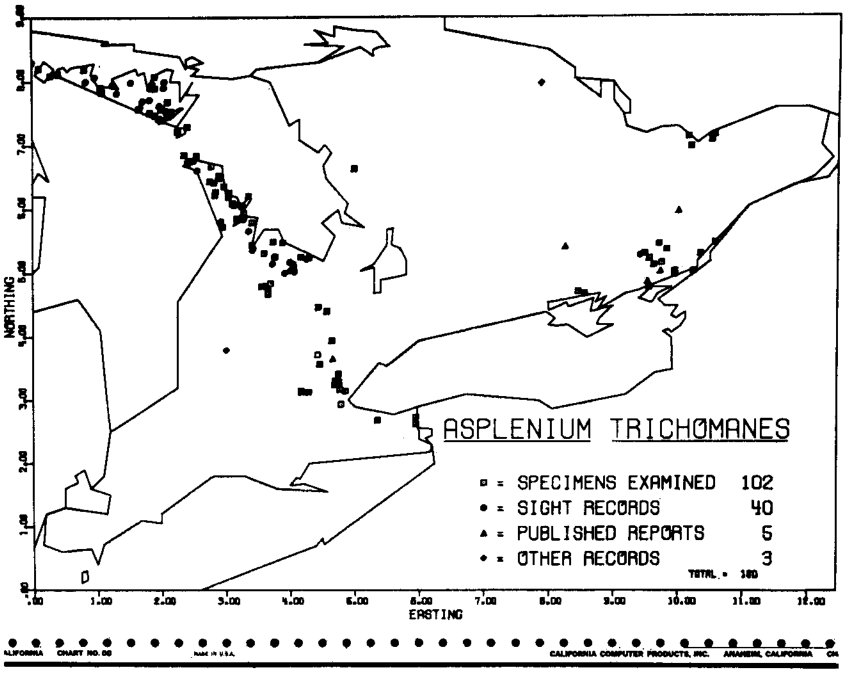

Fig. 2. Distribution records of *Asplenium trichomanes* mapped on an incremental plotter driven by a computer (from Soper, 1966). The outline map was also plotted by the computer but only a few hundred points were used for this version.

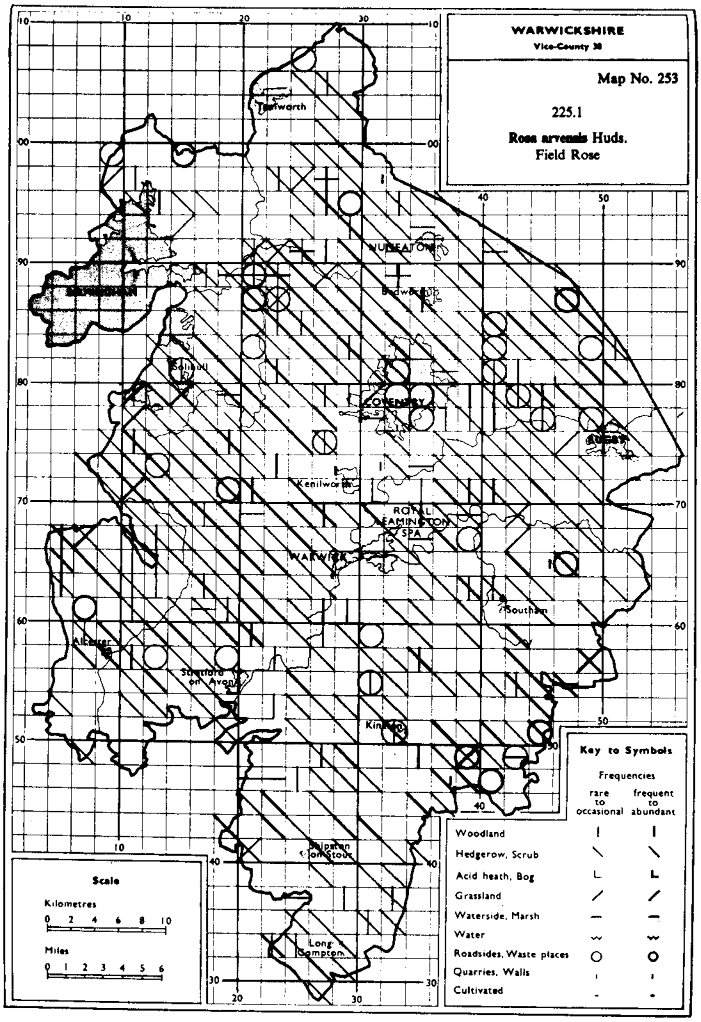

Fig. 3. Distribution of *Rosa arvensis* from Cadbury, Hawkes, and Readett (1971). This map was generated on an incremental plotter with the base map overlain by photographic techniques. Note the various symbols available to show habitat and the differences in line intensity to show abundance.

much more sophisticated distribution maps for the flora of the county of Warwickshire, England. Figure 3 shows the distribution map for *Rosa arvensis.* Note the various symbols which not only show distributional data, but abundance by the darkness of each symbol. In addition, the different symbols show the kind(s) of habitat where the species occurs. The species may occur in more than one habitat in one of the 2 km. square grids. This is shown by overplotting of habitat symbols (e.g., in Fig. 3, note the o with a slash which stands for both roadsides and hedgerows). This plotting was accomplished using an incremental digital plotter driven by a computer. These symbols are easily plotted with this equipment. To avoid problems of aligning a preprinted base on the plotter, two reference marks were made by the plotter in the same relative position on each plot. These reference points were then lined up with an overlay map of Warwickshire County before photographing the plots for publication. This assured that the points would be properly aligned. This is perhaps one drawback of this system if one wanted to produce maps on a real time service basis, but presents little difficulty if the final objective is a printed document such as a book.

Several other mapping projects have been proposed and are in various stages of implementation (see Beschel and Soper, 1970; Hastings, 1972). It appears that most of the mapping projects are resulting in a printed volume instead of being an active distributional data center where one can obtain real time or return mail maps made to order. Although books of maps such as the *Flora of the British Isles*, etc., may be of considerable value, I believe their value would be greatly enhanced if a data bank of distributional data was maintained such that current information would always be at hand.

Computer graphic Plotting in Studies of geographic Variation

In the past several years there has been an increased interest in the use of computer graphic plotting to analyze geographic variation. This has probably come about because of the larger, more diverse sampling in these studies and the ensuing, copious amounts of data generated. A mere plotting of geographic means is just not adequate to analyze a complex pattern of

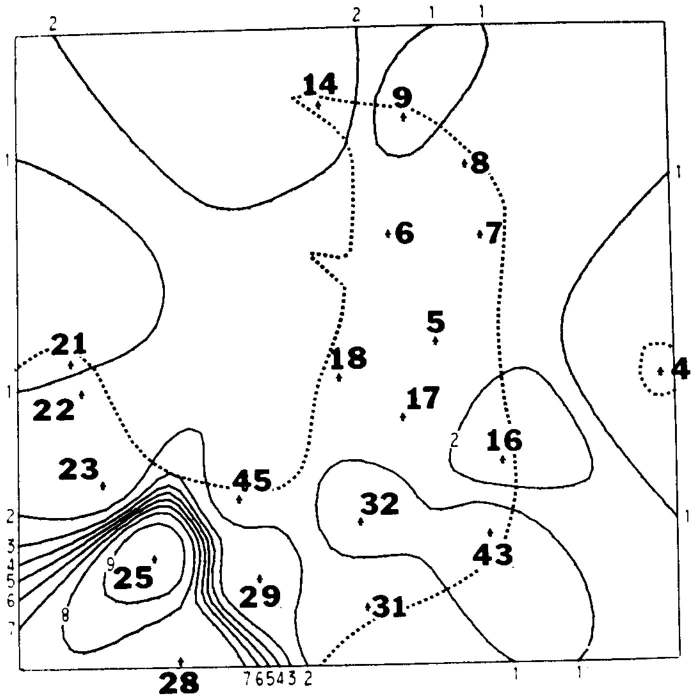

Fig. 4. A 2 dimensional contour map of populational variation of a terpene compound in natural populations of *Juniperus pinchotii* (from Adams, 1972). The dotted line (added by hand) shows the distribution of this taxon. This map was produced on a cathode ray tube (CRT) microfilm plotter.

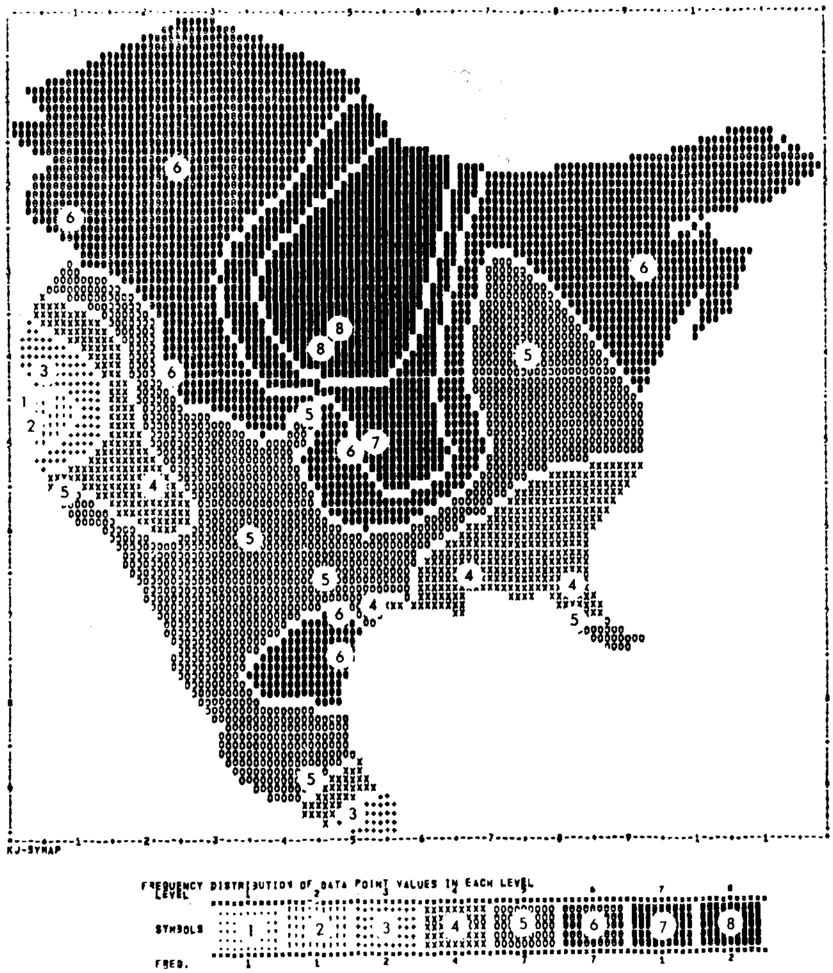

Fig. 5. A 2 dimensional shading map of size variation in male house sparrows (from Gould and Johnston, 1972). The various shades were made on a line printer (tabulator) by over-printing various characters.

geographic variation. New methods including contour mapping (2 dimensional and 3 dimensional), shading, contoured factor analysis, and surface trend analysis are now being used.

Perhaps the most straightforward computer graphic technique is 2 dimensional contouring of geographic variation. James (1970) analyzed populations of 12 species of birds and found the wing lengths to vary with climate as well as topographic features. Adams and Turner (1970) analyzed populations of *Juniperus ashei* Buch. by contour mapping both morphological and chemical characters on a geographic basis. Adams (1972) used contour mapping to analyze populational differentiation in *Juniperus pinchotii* Sudw. Figure 4 shows a contour map of the percentage of a terpenoid compound in populations of *Juniperus pinchotii* Sudw. (from Adams, 1972). The dotted line shows the distribution of *J. pinchotti.* The pattern of population differentiation is quite evident from this 2 dimensional contour map. One might overlay various climatic, soils, geology, etc., maps to attempt correlation of this trend with various factors.

Two dimensional maps have also been produced by a line printer (tabulator) to indicate geographical variation. Leith and Radford (1971) used shading to show differences in the phenology of dogwood in North Carolina. Dates of phenological events were correlated on a geographical basis with average minumum daily temperatures for January, February, and March. Gould and Johnston (1972) have used shading in the analysis of size variation in male house sparrows in North America (see Figure 5). Siccama (1972) has used overprinting to show spatial distribution of various species abundance. These maps are generated by overprinting symbols on a line printer to obtain the various shades. One problem inherent in shading is that the human eye can only discriminate between a relatively small number of shades. This is often not much of a constraint since dividing the data scale into more than 10 shades often leads to too much visual confusion. The use of color cathode ray tubes for mapping has been used but publication of the results presents a major problem.

Perhaps the logical step from 2 dimensional mapping is to 3 dimensional mapping. This is well illustrated by Pauken and Metter (1971) in their analysis of morphological variation in populations of the ribbed frog *Ascaphus truei*. Figure 6 (adapted from Pauken and Metter, 1971) shows a 3 dimensional map of morphological variation in *Ascaphus truei*. The "mountains" show areas of higher morphological variability and the low, flat areas show areas which are more uniform, morphologically. The vertical scale can generally be expanded to emphasize differences and the view can often be rotated to enable one to obtain a different perspective. For an excellent reference to 3 dimensional mapping and geographical data handling see Tomlinson (1972). Three dimensional mapping may aid in the grasping of geographical variation at a single glance but some of the relationships are generally hidden and visual correlation with edaphic and climatic factors is very difficult. For a rapid, visual image of variation the

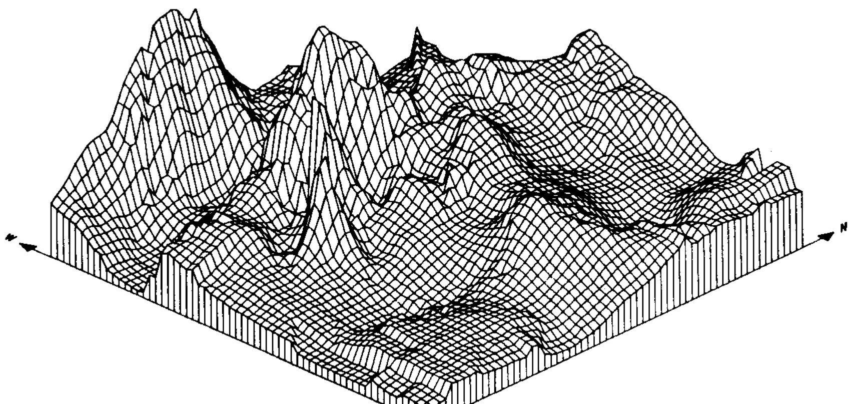

Fig. 6. A 3 dimensional map of morphological variation in *Ascaphus truei* (from Pauken and Metter, 1971). These kinds of computer graphics allow one to easily grasp the overall trend but are more difficult to correlate with geographic differences and environmental variations.

3 dimensional maps are better than the 2 dimensional contour maps but for detailed analyses I believe the 2 dimensional maps are of more use.

The use of contour mapping to show variation in factors (obtained from Factor analysis or from principal components analysis) has not been utilized very much but deserves some attention since population differentiation of many characters can generally be partitioned into a few factors. The visualization of these trends involving many characters may represent responses to various selection pressures and these can often be correlated with geographic variations in edaphic and climatic variables. An early example of this use of computerized contour mapping of factors is that of Fisher (1968) in his study of faunal distributions in Kansas. Figure 7 (adapted from Fisher, 1968) shows a sixth degree trend surface (a sixth degree polynominal of course is not exactly a contour map of the

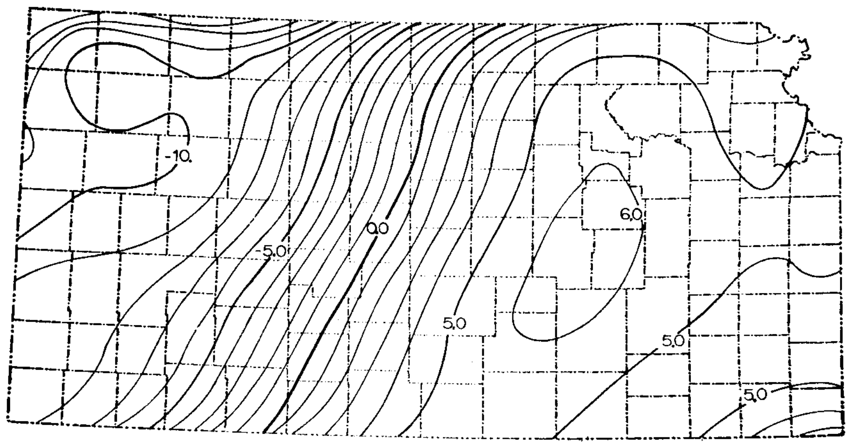

Fig. 7. A contour map of a sixth degree trend surface of a factor extracted from faunal distributional data (adapted from Fisher, 1968).

data but for our purposes, approximates the contour surface) of a factor extracted from faunal distributional data. This pattern of variation in species distributions is similar to the rainfall pattern in this area and thus precipitation is thought to be a significant factor in explaining the distributions of some of these species. Although not too much work has been done with computerized mapping of factors on a geographical basis, this area is likely to become very important in the future of systematics.

Present Applications of computerized Distribution Mapping

In my own laboratory we have been involved with computerized mapping of plant distributional data for approximately 4 years The Rapid Access Plant Information Center (RAPIC) of Colorado is located at Colorado State University, Ft. Collins, Colorado, and is funded by the Colorado State Experiment Station. The center of RAPIC is the Rapid Acces Plant Information Retrieval (RAPIR) system. RAPIR is core independent, allows new entries without recompiling the data bank and most importantly has extensive mapping capabilities. The RAPIC project is entering approximately 160 data descriptors for each of the estimated 3000 species of vascular plants in Colorado. An important consideration in the development of this data bank and systems programming has been the applied user such as foresters, county extension agents, land use planners, weed control districts, community colleges, etc., as well as the traditional taxonomic community. Since the purpose of this paper is not to discuss information retrieval systems, I would like to discuss only the retrieval and mapping of data from the RAPIR system.

Three kinds of distributional data records are stored for each species:

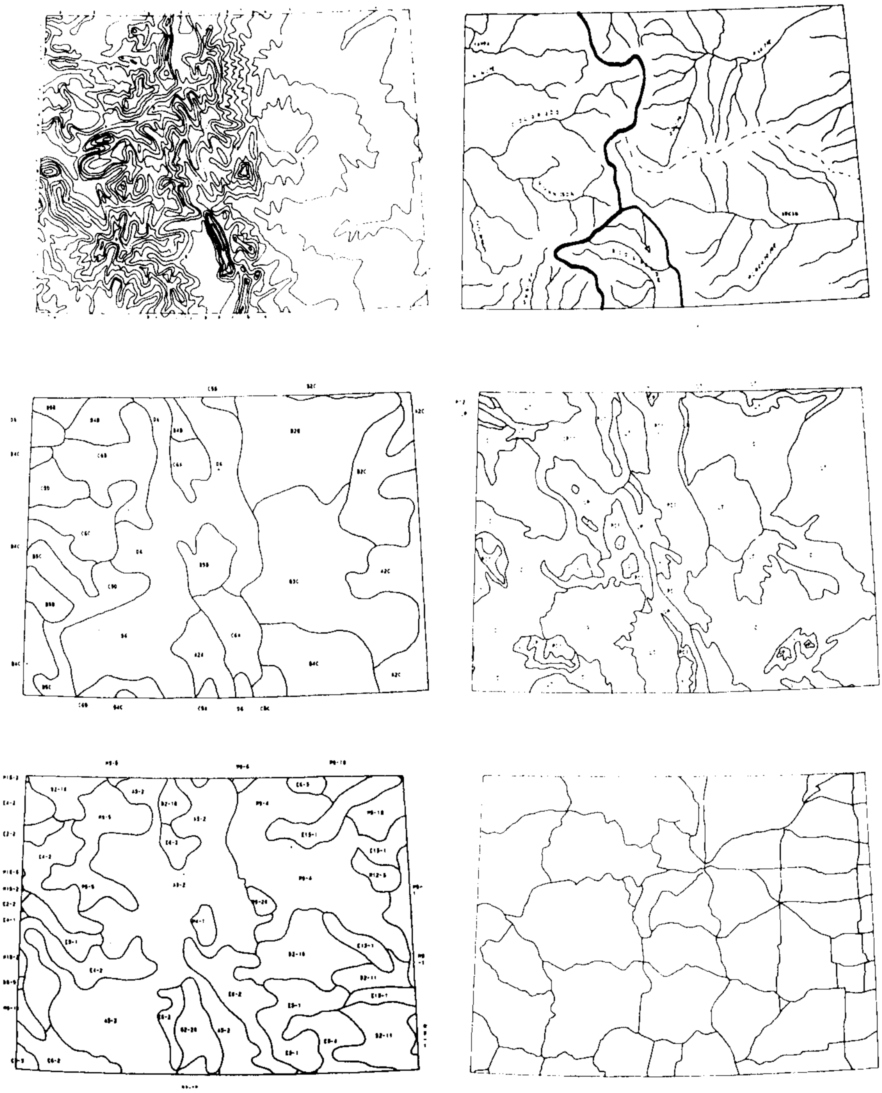

Fig. 8. Computer generated maps of elevation (upper left), drainage basins (upper right), land surface forms (middle left), surface geology (middle right), soils (lower left), and state highways (lower right) from the RAPIR system. These maps are each generated on a cathode ray tube (CRT) and photographed automatically onto microfilm. One to three seconds of central processing time are required to generate each of these maps. The instructions to generate each of these maps are stored in records on magnetic files.

1. Distribution based on vouchered specimens;
2. Distribution based on reliable records, such as ecological studies, sight records by monographers, etc.
3. Distribution records based on unconfirmed, doubtful reports.

For each taxon, a separate computer file is kept for each of these categories of distributional records. These distributional records are stored in a compressed computer format on magnetic disk but the original data can be converted to latitude and longitude for plotting on a sub-continental or continental basis. In addition to the distribution maps for each taxon in the data bank, there is also a Base Map File (BMF) of 24 maps for Colorado. These maps include various physical and environmental factors such as annual rainfall, warm season rainfall, various average temperatures, length of growing season, geology, soils, etc. These maps are also stored in a compressed computer format onto magnetic disk. Figure 8 shows 6 of the maps in base map file. These are each retrievable by calling them from the RAPIR

Fig. 9. A computer generated map of North America showing states and provinces. This map was generated in the same manner as those in Figure 8.

system in a simple English sentence. These maps were generated onto the surface of a cathode ray tube (CRT) under the direction of a CDC 6400 computer. A camera is mounted onto the face of the CRT and regular 35 mm pictures are taken (generally called microfilm plotting). Each of these maps takes about 1 to 3 seconds of central processing (CP) time. The maps were digitized on a stereo comparator using a 35 mm color slide of the base map. All of the base maps were taken from the U.S. National Atlas, 1970 edition, when possible. The most complex map, the relief map at 1000 foot intervals, took about 6 hours to digitize and uses about 18,977 computer instructions to generate. But we feel that this is probably too many points for our scale. The microfilm is normally printed by rapid copy microfilm printers which produce a hard copy in about 10 seconds. The greatest delay is in obtaining the microfilm from the computer center, which takes about 3 hours. Various size lens can be used with microfilm printers but the prints are not normally larger than 8½ inches by 11 inches. Since nearly all libraries have microfilm readers (and printers), the microfilm can be sent by letter to the user for printing as desired. Although RAPIC has only been developed for Colorado, larger areas can be digitized and stored. Figure 9 shows an outline map of North America with state and province boundaries. This map requires about 80,000 computer instructions and took about 35 CP seconds to generate on the CRT.

All of the maps in BMF may be overlaid in any combination. Figure 10 shows a computer generated map of the counties of Colorado overlain with the

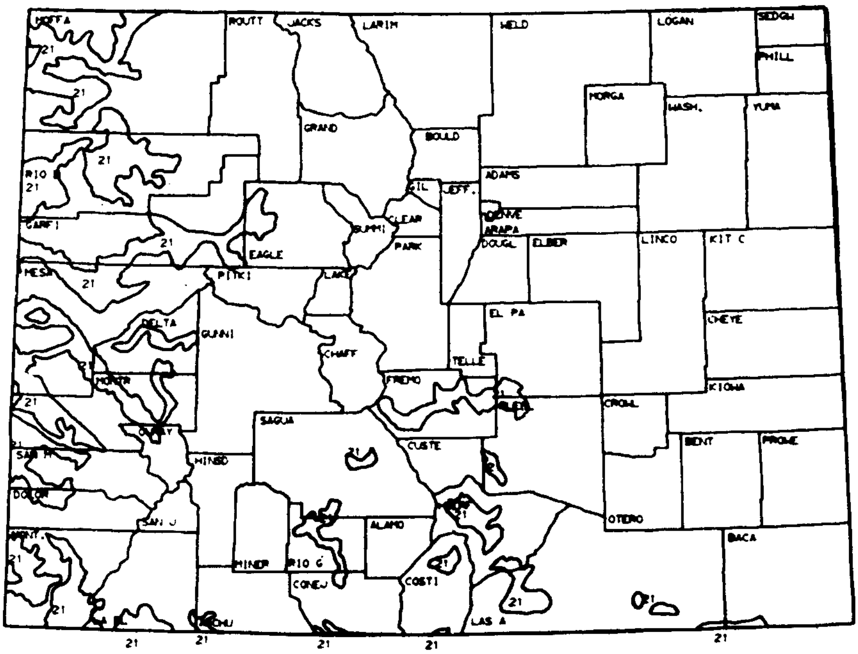

Fig. 10. Two maps from base map file (BMF) plotted on the same microfilm frame. The pinyon-juniper woodlands has been plotted onto the county map of Colorado to show areas in the counties with this particular type vegetation. Any combination of maps in base map file may be overlain.

computer generated map of the pinyon-juniper woodlands. Data such as this may be useful in land use planning decisions, weed control by counties, or even to the traditional ecologist or taxonomist.

Perhaps the most significant characterictic of the RAPIR is the ability to plot any or all of the distribution records for a taxon onto any or any combination of the base maps in base map file. This capability is shown in Figure 11 where the queries were:

FIND, ALL VOUCHER RECORDS OF SPECIMEN WITH GENUS, DESCHAMPSIA AND SPECIES, CAESPITOSA*
MAP ONTO SOILS*

These queries have caused a retrieval of the voucher distribution record file for *Deschampsia caespitosa*, plotted the soils maps for Colorado from BMF, and plotted each collection point onto the soils map. Examination of Figure 11 reveals that all of the vouchers of *D. caespitosa* have been collected in the high, moist mountain soils (A3-2). Areas of over collecting are very apparent as well as areas of under collecting. Correlations with any of the other maps in could also be examined by merely asking additional queries such as: MAP ONTO AVERAGE RAINFALL*, etc. A detailed examination of the RAPIR language is beyond the scope of this paper and will be covered in another paper.

Since the distributional records are built into the RAPIR data bank (by indirect addressing), one can also ask powerful synthetic queries. For instance, suppose one wanted to see the general distribution of all species of *Deschampsia.*

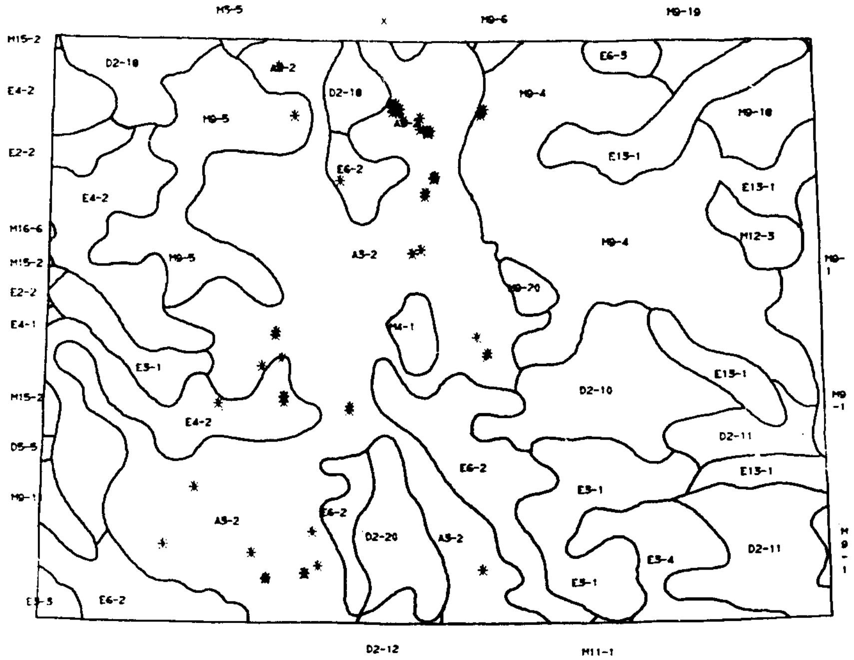

Fig. 11. The vouchered distribution records of *Deschampsia caespitosa* plotted onto a soils map of Colorado. Note areas of overcollection and the correlation with the A3-2 soil (soil types from U.S. Nat. Atlas, 1970).

The query would be:
FIND, ALL VOUCHER RECORDS OF SPECIMEN WITH GENUS, DESCHAMPSIA*

This could be followed with a MAP ONTO *map name** to generate a map of all the vouchered specimen of Deschampsia on the chosen map from base map file (there is a map of just the Colorado State outline for use with complex distributional records). One might also ask for the distribution of all noxious weeds by a query such as: FIND, ALL VOUCHER RECORDS OF SPECIMEN WITH WEEDINESS, NOXIOUS*. To the author's knowledge, this is the only mapping system which will allow one to map distributions based on various plant characteristics in addition to using scientific names. The potential number of users of this system is much greater since maps can be generated specifically to the user's needs (i.e., cattlemen may need a map of all poisonous plants which are grasslike; wildlife managers might want a distribution map of plants which are both good forage for wildlife and shrubby; etc.). The ability to map any combination of distributions according to the user's desire is the first step in the direction to having maps custom generated on a real time or return mail basis.

All of the mapping capabilities mentioned aforehand on the CRT (microfilm plotting) are also available in flatbed plotting on a Calcomp plotter such that maps can be generated in sizes up to several feet square.

Fig. 12. A base map of slopes in the composite mapping system (CMS) where the steeper slopes have been assigned higher values (darker shades) for this particular run. This map was generated on the CRT. The mesh size is 120 by 120.

Fig. 13. The same base data (slopes) are used in Figure 12 with shading levels assigned such that the steeper slopes are the lighter shades. Any shading level may be assigned to any value of the base data.

Present Application of composite overlay Mapping

A relatively new technique which has not been used in systematics is that of composite overlay mapping (often called composite mapping). This technique has been used for several years in land use planning. A geographical area is divided into grids, each of which contains certain base information. For instance, suppose your geographic area is a county. For any particular grid cell you might inventory for soil type, average rainfall, geological formation, vegetation type, slope, etc. The data is collected and stored unbiased. That is, slope might be divided into 10 classes encompassing all of the range within the county. The fact that the grid cell might have a slope of 3 (on a scale of 10) is merely stored in the computer with no pre-judgement as to whether that particular degree of slope is "good", "bad", useful, or useless. The value of any particular data state is not assigned until a question is formulated of the system. For instance, Figure 12 shows a hypothetical example of slope where the higher values (darker shades) were assigned to the steeper slopes. This grid is on a 120 x 120 mesh for the entire square and has been plotted onto a CRT (microfilm). The actual coded slopes (i.e., coded data values) remain stored on permanent files regardless of the temporary assignments made for this particular run. Figure 13 shows the same data base where the assignments have been made in just the reverse order (i.e., steepest slopes are the lightest shades). The various slopes do not have to be assigned differently since any combination of slope categories could individually or collectively be given the same assigned shading levels. Another weighted set of data is shown in Figure 14. This data might represent soil types where various types of soil have arbitrarily been assigned particular shades. The compositing of maps occurs when one calculates grid values for all maps considered simultaneously. That is:

Let X_{ij} = composite value for all maps at grid i,j

W_k = weight of map k in the composite function

A_{ijk} = assigned level of shading for the data value at grid i,j of map k.

Then:

$$X_{ij} = \frac{W_1 \cdot A_{ij1} + W_2 \cdot A_{ij2} + \ldots + W_k \cdot A_{ijk}}{\sum_k W}$$

The composite values, X_{ij}, are then rescaled to give the maximum shading differences upon output.

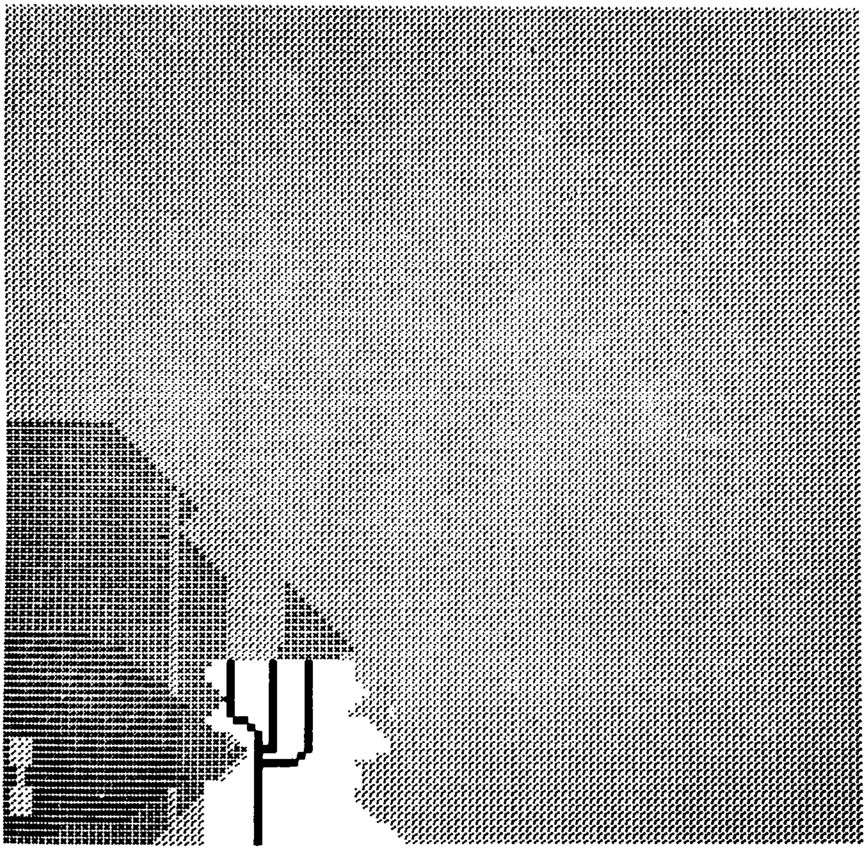

Fig. 14. Hypothetical soil types in an area with different shades assigned for this particular analysis (see text for discussion).

Suppose we have two maps to composite (Figures 12 and 14) and want to weight the slope and soil types equally having assigned shades as shown previously. Then:

$$X_{ij} = \frac{1 \cdot A_{ij1} + 1 \cdot A_{ij2}}{1 + 1}$$

The composite map is shown in Figure 15. Note that the areas of overlapping shading are reenforced. The overall weight of each map (factor) in the final composite can be given any value. This is shown in Figure 16 where the first map (factor = slope in this example) has a weight of 78% of the total function and the second map has a weight of 22% of the total function. Note the higher slopes become more significant in the total picture when the new weighting is used.

With our present composite mapping system we can composite up to 20 maps of factors. Since the number of data points is fairly large (14,400) for each map, the collection of data is a major problem. The use of automatic data collection equipment such as the Science Accessories Corporation *Graf Pen* has greatly aided in our data collection. Digitizing the initial data maps or factors is a large task. I believe that composite mapping will probably find its greatest use in studies of the flora or vegetation of a particular geographical area. If

Fig. 15. A composite map of slope and soils constraints where the original data was assigned as shown in Figures 12 and 14. Each of the base maps were given equal weight.

Fig. 16. A composite map using the same data and assignments as in Figure 15 except that the slope factor has been weighted as 78% and the soils as 22% of the weights. Notice the predominance of slope in this analysis as compared to Figure 15. See text for discussion and application.

one inventoried an area for various climatic and edaphic factors and then assigned shading levels to each value according to how this factor state affects a particular species, the weighted composite of the factors should show where the best species' habitat is located. This could then be checked from distributional data. Conversely, given the species distribution, one should be able to calculate the relative importance of the various edaphic and climatic factors upon the distribution of that species. Composite mapping may also be useful in the analysis of infraspecific variation, particularly when populational differentiation is related to geographical variation in environmental variables.

The composite map can also be made by overprinting on computer paper but due to line spacing of the type, the scale is somewhat distorted. Nevertheless, since this method is fairly cheap and fast, considerable overprinting will likely be used during the analysis phase of most studies.

Future Applications

The development of more interactive computer facilities will likely lead to new developments in interactive computer graphics (i.e., cathode ray tube displays). Already one can query and retrieve data over ordinary telephone lines, but the rates of transmission seems to have limited the transmission of computer graphic displays on a real time basis. A breakthrough in this area would certainly provide impetus for the development of national mapping centers where distribution maps could be generated on a real time basis and plotted onto any number of base maps for the user. One possibility that might be developed is the use of a system such as used by newspaper wire services to transmit photographs, but to the author's knowledge is not commercially available. An interesting example of an on-line (direct linkage) application of computer graphics is presented by Kendrick (1972) in the identification of the didymosporous Hyphomycetes.

There appears to be little doubt that computer graphic plotting and mapping of data in systematics has made a significant impact and will become an ordinary tool for most systematists by the end of the next decade.

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