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An IconMap-based exploratory analytical approach for multivariate geospatial data

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Abstract This paper discusses an iconmap-based visualization technique that enables multiple geospatial variables to be illustrated in a single GIS raster layer. This is achieved by extending the conventional pixel-based data structure to an iconic design. In this way, spatial patterns generated by the interaction of geographic variables can be disclosed, and geospatial information mining can be readily achieved. As a case study, a visual analysis of soil organic matter and soil nutrients for Shuangliu County in the city of Chengdu, China, was undertaken using the prototype IconMapper software, developed by the authors. The results show that the static IconMap can accurately exhibit trends in the distribution of organic matter and nutrients in soil. The dynamic iconmap can both reflect interaction patterns between organic matter and the nutrient variables, and display soil fertility levels in a comprehensive way. Thus, the iconmap-based visualization approach is shown to be a non-fused, exploratory analytical approach for multivariate data analysis and as a result is a valuable method for visually analyzing soil fertility conditions.

Keywords iconmap, soil fertility, visualization, icon blocks, multivariate geospatial data

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1 Introduction

One of the main aims of the geographic information science community is to process huge volumes of geospatial data to extract specific features and display their geographic patterns using visualization tools [1–4]. Conventional GIS raster images generally are constructed by assembling groups of pixels as mosaics; at each pixel location, only one geospatial attribute can be displayed at a time [5,6]. In order to represent multiple geospatial variables in a coordinated way, three data layers are often composed and expressed in the form of composite false-color images by image processing packages; alternatively, a number of layers can be converted into a fused composite index using a weighted combination through cartographic overlay analysis, so as to express the synergistic effect of these spatial variables. Although the two methods can, to some extent, give a coordinated representation of multiple geospatial variables, they cannot satisfy the needs of increasing complexity in spatial data and data analysis. For instance, it is impossible to determine the information carried by original data layers once a composite index has been fused, or which

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variables play a dominant role [6,7]. Therefore, it is necessary to continue to explore new techniques and methods for visualizing multiple geospatial variables on the basis of single raster layers.

Currently, scientific visualization techniques include geometric, icon-based, pixel-based, three dimensional, dynamic, virtual or enhanced reality [5,8–11], service-oriented [12] and hybrid visualization methods [13–15]. The icon-based method is widely applied in computer interface designs [16–18], visualization in scientific computing, physical experiment simulations [19–21], medical diagnoses [5], and musical studies [22]. Early applications of icons or glyphs for visualization were mainly used to visualize the similarities or clusters in point data sets. For example, "Chernoff Faces" display data using cartoon faces by relating different variables to different facial features [23]. In cartography, icons are also used as cartographic symbols, such as directional icon symbols [9,15] that are common in tourist maps [24]. The icon-based method now has been extended and applied to the visualization of multivariate geospatial data [5,6]. A GIS-icon concept has been created and an iconmap-based visualization technique has been developed which is capable of visualizing multiple geospatial variables and can be applied, for example, to the study of vehicle accessibility in the Las Vegas area of the United States [6]. The iconmap-based visualization technique is a non-fused co-visualization approach. This means that it can effectively express a number of correlated geospatial variables, thus solving the problem with conventional GIS raster layers that cannot represent multiple variables at a single pixel location due to the simple raster structure. The method provides a reliable and viable technique for exploratory analysis of multiple geospatial variables [5–7,9].

In recent years, both research and practical work concerning formula fertilization has increasingly required more understanding of soil organic matters, nutrients and fertility. However, relevant work has often been focused on the spatial variability of a single variable; research on soil fertility involving multiple variables has continued to use the conventional classified composite index method, which involves fused visualization. Currently, no research on icon-based visualization of soil composition variables is available, and soil fertility is usually characterized by several multivariate variables such as soil organic matter (OM), total nitrogen (TN), available nitrogen (AN), available phosphorus (AP) and available potassium (AK). Therefore, this study examines the usefulness of an iconMap-based visualization technique for analyzing soil organic matter and nutrients. Two categories of icons: static and dynamic, are designed and used to explore the spatial patterns inherent in multivariate geospatial data or variables of soil organic matter and nutrients. A comparison with the conventional composite approach will also be presented.

2 Principle of the iconmap-based visualization technique

According to Horton [18], an icon is a symbolic representation or small piece of image correlated to data. The function of an icon or glyph is "to show the key features or characteristics of a data domain in a symbolic way" or to act as a symbolic representation of one or more variables of a data set [5,18]. Unlike conventional uses of icons, each icon in the iconmap-based technique includes not only a meaningful graphic design, but it also corresponds to a certain geospatial location - a development of the conventional icon representation in a GIS raster environment [6,7]. As a graphic element, the icon extends the conventional dual image structure "image-pixel" to a three-tiered image structure "image-icon-pixel" in a GIS raster data layer. Therefore, each icon consists of several icon elements, and each icon element consists of several pixels and bears a certain geometric shape and attributes. Consequently, if the geometric attribute of an icon element does not change with different values of the variable, but its color varies to indicate the various values of the data layers the icon represents, then it is called a "static" icon. In contrast, if the geometric attribute (i.e., the length of a bar) of an icon element does change with different values of the data layers, then it is called a "dynamic" icon. As shown in Figure 1, (a) represents a static icon consisting of three icon elements in which each element can represent a geographic variable or data layer; for example, "1" can represents fractional vegetation cover (FVC), "2" the topographic gradient, and "3" the road accessibility. (b), (c) and (d) form a dynamic icon sequence, with each icon element's graphic shape (designed as a bar here) changing in length with the quantity of the data layer it represents. There are eight icon elements (numbered "1" to "8") and one background (numbered "9") in all for this dynamic icon design. Note that the graphic shape of a static icon will remain unchanged;

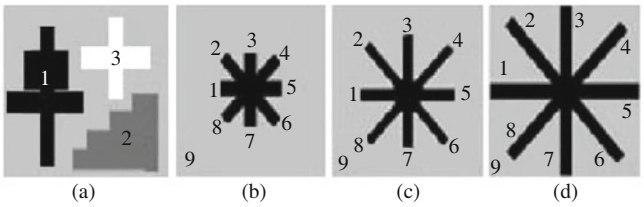


Figure 1 Icon templates: examples. (a) Static icon, three icon elements designed in the template with each graphic design linked to a data layer. For example, 1 to vegetation, 2 to topographic gradient, and 3 to road accessibility; (b), (c), (d) form a three-level dynamic icon sequence; each of the 8 icon graph "bars" can be related to a specific geospatial data layer; the area numbered "9" is the icon background.

changes in its color are related to changes in the data set it represents, providing a way to show the spatial or temporal distribution pattern of geospatial variables. For example, in Subsection 3.2, a color sequence from black to red indicates that the content of total nitrogen (TN) in the soil changes from low to high.

An icon image map can be created by populating each pixel of the input data layers into an iconic representation using the selected icon template(s). The geospatial data layers are analyzed by an image map structured on the icon template, thereby expressing multivariate geospatial variables in a single GIS raster layer. For instance, by using the static icon template (a) in Figure 1, the three data layers consisting of fractional vegetation cover, road accessibility and topographic gradient can be projected as icon elements 1, 2 and 3 respectively, and the relief information generated from the DEM data can be represented as the background of the icon template. Thus, the four geospatial variables can be displayed in one GIS raster layer, termed an 'icon image map'. This process of icon image map generation can be automatically executed with the IconMapper system, a prototype software system developed by the authors to implement the visualization technique. In addition to displaying multivariate geospatial data in one raster layer in a non-fused way, the icon itself acts as a graphic design with a certain geometric shape that can "visually" represent certain thematic variables and convey more information to the map user than a pixel-based image alone [5,6,20]. The interactions between icons and between icon components can produce visual effects that can display distinct spatial distribution patterns as a result of interactions among the geospatial variables. The discussion in Section 3 focuses on the example of creating icon image maps of soil organic matter (SOM) and soil nutrients, thereby using the principles of icon image mapping as a new technique for visualizing spatial patterns of soil fertility.

3 Study area and method

The study area is located in the central part of Shuangliu County in the city of Chengdu, Sichuan Province, China. It consists of 11 townships and is a state-level demonstration area for the soil testing and formulated fertilization (STFF) program that is being implemented by the Chinese Ministry of Agriculture. Soil samples were collected according to Sichuan Provinces Technical Regulations for the Soil Testing and Formulated Fertilization Program. Geographic locations of sampling sites were collected by GPS. Each soil sample is actually an average of five samples taken at depths of 0–20 cm, centered on one point. A total of 836 sample points were obtained for the study area. The soil samples were analyzed in the laboratory for five variables that can characterize soil fertility for agriculture, i.e., soil organic matter, total nitrogen, available nitrogen, available phosphorus and available potassium. As the soil organic matter and soil nutrients are the result of the complicated interaction and historical evolution of soil type factors, topography, climate, surface coverage and farming system, an understanding of their distribution patterns will be significant for prescribing multivariate fertilization formulae. Therefore, a demonstration of the usefulness of the proposed visualization technique for the exploratory analysis of soil fertility offers a new and helpful tool for understanding these patterns.

3.1 Data preprocessing

In order to prepare soil fertility data layers for exploratory analysis by the iconmap-based visualization technique, the soil sample data need to be preprocessed with spatial statistics and interpolation methods, so as to obtain the spatial distribution pattern of the soil organic matter and soil nutrient variables. GIS raster data layers of soil organic matter and soil nutrient contents were generated by means of spatial interpolation using both kriging and disjunctive kriging methods, as provided by the geo-statistical analysis function in the ArcGIS system. Obviously, the main purpose of this preprocessing is to convert discrete point data sets into continuously distributed thematic layers. The paper soil type map and topographic map of the study area were also digitized to obtain an administrative boundary and a soil type map with the ArcGIS 9.2 package, and registered to the same geographic coordinate system as the five SOM and soil nutrient data layers. After data preprocessing, representative icon templates were designed according to the characteristics of the geographic multivariate data for visual analysis. Then the iconmap-based visualization approach was applied to map each pixel of the soil variables into a patterned icon block, which produced the icon image map.

3.2 Designing the icon template

The design of the icon template plays a critical part in the effectiveness of a visualization. A 'good' icon design can effectively and visually express the interaction among multivariate data, and as a result displays the spatial segregation and patterns of such interaction in both macro and micro scales. Each icon template consists of two parts: icon graphic elements and background (Figure 1). The icon elements consist of graphic designs representing multivariate geographic data, where each icon element in its turn consists of a series of pixels carrying specific geometric shapes and attributes. The background is defined as the pixels that are not part of the icon element; they can have an attribute that can also be related to a geographic variable - or they can just be left as blank pixels. Note that the icon will not have an attribute value of its own; rather it will be a graphic symbol representing the geographic variables. The color assigned to the icon element during the design stage will not be a part of the computing or final display, but is used for differentiating the shapes of different icon components. The color and attribute displayed in each icon block of the final icon image map are projections of the corresponding pixel colors of the data layer represented by each icon element, and they reflect the changes of the pixel value of the geospatial data layers. In this study, the static icon template consists of 10×10 pixels. Five icon elements are used to represent soil organic matter, total nitrogen, available nitrogen, available phosphorus and available potassium, and the icon background is assigned to the soil type data layer. To ensure the final visual effect, the number of pixels for each icon element in the icon block should be approximately the same where possible, in case inconsistencies are created in the icon components due to size differences in the geometric graphs. In this study, the design of the static icon template uses 16 pixels to represent the soil organic matter, and the other four icon elements are all graphs consisting of 15 pixels. The background of the design has 24 pixels, conforming to the above-mentioned icon template design principle. The sum of all the pixels of the icon elements and background is 100, the exact size of the 10×10 icon. The static icon element remains unchanged in its geometric shape, with only the color changing in gradient following a change in the value of the variable or data layer it represents. Such change is inherited from the color in the pixel that corresponds to the data layer represented by the icon elements. Therefore, before undertaking visual modeling to produce an icon image map, it is necessary to assign a color sequence to each GIS raster data layer which was preprocessed in the previous section, to indicate the spatial segregation of that variable. In fact, this process can also be understood as using color for visualizing a single geographic data layer under the GIS raster environment, to indicate the spatial

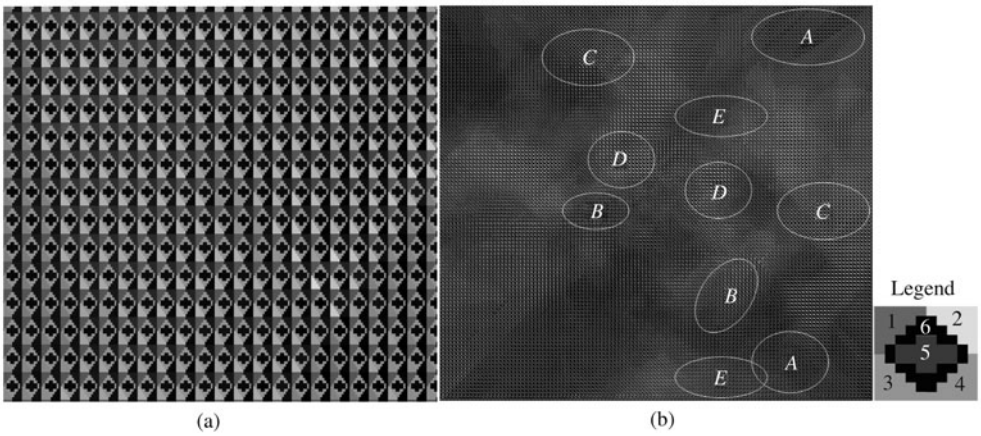


Figure 4 Portion of the static icon image map in the study area. (a) A macro-level view; (b) a local micro-level view. 1: TN; 2: AN; 3: AP;4: AK; 5: OM; 6: background.

3.3 Visual modelling: generating icon image maps

After the development and design of the icon template and colorization of the icon component data layer, visual modeling can be conducted to generate the icon image map. The templates are used to convert the values of each pixel in the preprocessed data layers to the value of the icon element at that location. For the static icon, the geometric shape of each icon element will remain unchanged, but its color will change with the data value of each pixel; for the dynamic icon, the geometric shape of each icon element (e.g., the bars as in Figure 3) will change in length with the value in the pixel location of the data layers that they represent. The color of the icon element is also inherited from the color of the pixel at that location. Since each pixel of all the original soil organic matter and nutrients data layers will be populated into an final icon block, such conversion is rather time consuming and none of the currently available commercial GIS software has such a function yet. Therefore, in this study, the prototype system IconMapper specially developed by the authors is used for the creation of the icon image map using the designed icon templates and the six preprocessed multivariate data layers. The design of icon templates can be completed using GIS raster software or a raster graphing tool, whereas visualization modeling and the generation of the icon map can be completed automatically using the prototype software. The software system also provides some supportive tools to help design the icon templates (i.e., testing the dynamic icon sequence), such as previewing tools (i.e., quick generation of a small portion of icon image map) and interactive query tools.

4 Results and analysis

4.1 Static IconMap

The areas of high soil organic matter and nutrient contents can be visualized effectively in static icon images at the macro-view level (Figure 4). Following the icon component coloring rule, the bright blue area labeled A in Figure 4(a) indicates that the organic matter is rich. Similarly, the reddish color at area B indicates the high content of total nitrogen, the greenish color at Area C indicates high levels of available nitrogen, and the yellow and magenta of areas D and E indicate regions with high values of available phosphorus and available potassium. By referring to the data layers represented by the icon elements in Figure 2, it is clear that the distribution pattern of each icon element shown in the static icon map is consistent with a single variable, and it can adequately reflect the synergistic information of multivariate data in one GIS raster image layer. In addition to the macro-level patterns of soil organic matter and soil nutrients, the static icon image map can also visually reflect interactions and relationships among the geographic variables at micro-levels. Figure 4(b) illustrates a small portion of the static icon

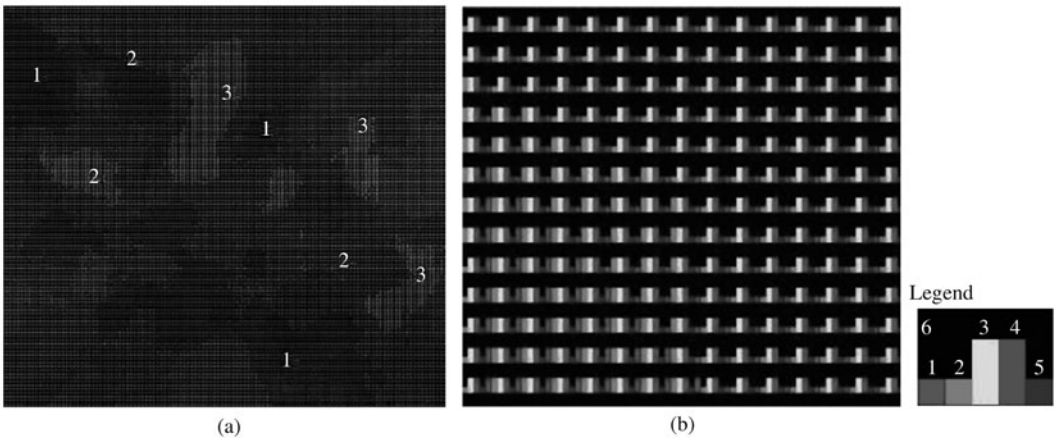


Figure 5 Portion of the dynamic icon image map in the study area. (a) A macro-level view; (b) a 1:1 micro-level view; 1: TN; 2: AN; 3: AP; 4: AK; 5: OM; 6: background. Area "1" is dominantly magenta, indicating a high AK content (colored magenta in the data layer in Figure 4); area "2" is dominated by green, indicating a relatively high content of AN in places represented by the second icon element; area "3" is dominated by red and yellow, showing there are high contents of AP and TN.

map at a scale of 1:1 (a zoom-in of area B on Figure 4(a)). The bright red and yellow colors of the icon elements indicate total soil nitrogen and available phosphorus in this area, according to the design of the static icon template. The colors blue, green and magenta of the other three icon components: organic matter, available nitrogen and available potassium, are relatively dark in the area, corresponding to the low content of these three soil nutrients. The patterns show that the total nitrogen and available phosphorus in the soil are high and the main contributors to soil fertility, and in this area organic matter content is relatively low. Thus, effective measures are called for that can increase the organic matter content so that soil fertility will not keep dropping.

Static icons reflect patterns of variation in each icon element through color changes, with black corresponding to the lowest concentrations of all elements. Therefore, the intensity of colors in the icon image map as a whole is unable to provide quantitative values, with the exception of relatively high and low values. For better visualization and analysis of multivariate data soil fertility, dynamic icon maps are required.

4.2 Dynamic IconMap

The dynamic icon template designed above was input, along with the soil nutrient data sets, into the IconMapper system. The link between the icon elements and the data layers they represent was built using an index file. The projection and conversion of the GIS raster layers to a single icon-based image was then completed to produce a "patterned" icon image map. As mentioned above, and in contrast to the static icon image map, the graphic attribute of each element of an icon block changes with the pixel value of the data layer it represents. The icon image map produced with the IconMapper system is shown in Figure 5. Thus, taken together, the changing icon graphs and their colors may present visual differences and exhibit spatial distribution patterns inherent to the distribution of soil organic material and nutrients. Figure 5 shows a portion of the icon image map for the study area as created by the IconMapper system for analysis of the visualization effect. Considering the dynamic icon template, the area indicated by "1" in Figure 5(a) is dominated by magenta colors, indicating that the area has a high level of available potassium (colored in magenta in this data layer in the preprocessing stage). The area indicated by "2" is dominantly green, indicating a relatively high content of available nitrogen (represented by the second icon element). The area indicated by "3" is dominantly red and yellow, corresponding to high contents of available phosphorus and total nitrogen (represented by the first and the third icon elements). Other areas that do not show distinct color effects are regions with low overall soil nutrient levels, and with low levels of both soil organic matter and soil nutrients. In contrast, in the brightly colored areas, there are

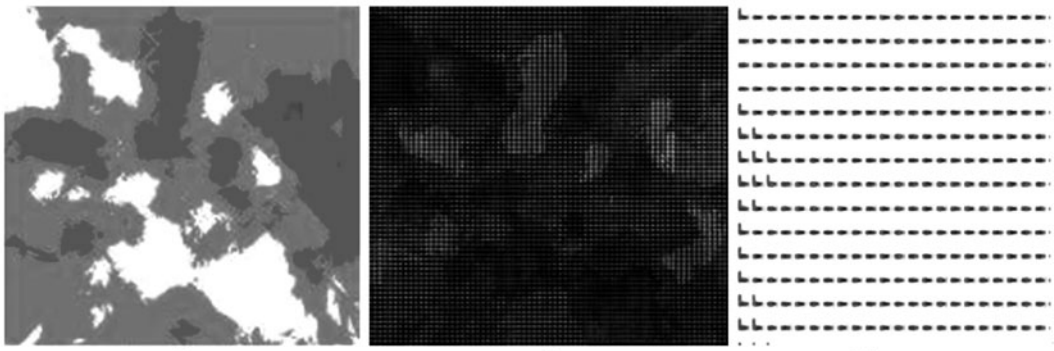
fewer background (grey) pixels, with the pixels for icon elements dominating in number. In other words, there is high in soil organic matter and soil nutrient content, with overall fertility levels on the high side. An enlarged view of a part of the icon image map shows that each icon changes according to the variable values. The lengths of the bars reflect the content levels of the elements at different pixel locations. Figure 5(b) shows a low-to-medium level of soil fertility in this area, with available phosphorus and available potassium at a medium content level, and generally low contents of organic matter, total nitrogen and available nitrogen. In the southwest corner, however, apart from the low organic matter content, all other soil nutrients are at a medium level as indicated by medium-sized bar lengths. Compared with the static icon image map, the dynamic icon can directly show the distribution pattern of soil variables by changing graphic shapes to give better visual effects. The graphic shapes help to analyze synergistic relationships among the variables and to uncover restraining factors for soil fertility, thereby offering practical support for agricultural production.

4.3 Comparison of "non-fused" and "fused" visualization approaches

The iconmap-based visualization technique is a "non-fused" approach for qualitatively and semi-quantitatively visualizing a number of geographically correlated quantitative spatial variables. To analyze synergistic relationships between multivariate geospatial variables in a conventional GIS raster model, these multivariate data layers have traditionally been integrated using weighting functions or combined into a comprehensive index that is presented as one GIS raster image layer. This is called a "fused" visualization analysis for multivariate data. In order to verify the usefulness of the iconmap-based visualization technique in reflecting the distribution of soil organic matter and nutrients in the study area and revealing the soil fertility patterns, a conventional fused method, or integrated index, was applied to the same data sets. A comparison between the iconmap-based and fused index approaches is presented in this section. The integrated fertility indicator (IFI) can be derived and used to represent the soil fertility level by a weighted combination of the five soil organic matter and nutrients data layers. Considering that the interpolation of soil organic matter and nutrients is closely related to its variation, the variation coefficient method is therefore applied to determine a weighting index. The main steps are as follows. First, the standard deviation of the indicators is calculated to reflect the absolute variation of the factors; Second, the variation coefficients of factors are calculated, to reflect the relative variation of the factors; The third step is to normalize the variation coefficients of the indicators to obtain their weights; Finally, the weighted values of soil organic matter, total nitrogen, available nitrogen, available phosphorus and available potassium are determined as 0.148, 0.153, 0.172, 0.311 and 0.216, respectively. The indicator IFI is calculated for the entire study (Figure 6(a)).

Comparing the IFI image (Figure 6(a)) with the dynamic icon image map (Figure 6(b)) shows that the white and light-red patches in the IFI map (indicating low values of IFI) exactly match the dark patches at the same locations in the dynamic icon image map, while the red patches in the IFI map (showing high IFI values) also match the brighter colored (indicating icon elements bearing longer bars) patches in the dynamic icon image map quite well. This visual comparison indicates that the icon image map used to visualize soil organic matter and soil nutrients is consistent with the IFI obtained by the conventional fused approach; both can adequately reflect the soil fertility condition. However, the IFI method cannot characterize which elements or variables have a high content at a given location; the icon image map is capable of this by checking the dynamics of the graph for each icon element on the micro-view level (Figure 6(c)), thus offering more information to the user. This is the main advantage of the "non-fused" approach.

Further analysis will show that the distribution patterns of the soil variables given by the dynamic icon image map and by the IFI map do not give one-to-one matches, indicating that there is a certain degree of difference between the methods for visualizing multivariate geospatial data. Where the conventional fused method is concerned, it is the different methods for determining the weight factors that impact strongly on the final IFI result; any synergistic relationships among the variables are not directly revealed. On the other hand, the iconmap-based dynamic icons will not only reflect the integrated soil fertility level at a macro-scale, but will directly indicate synergistic relationships between the soil organic matter and



(a) (b) (c)

Figure 6 Comparison between non-fused and fused visualization methods. (a) IFI integrated index: white and light red indicating lower fertility levels and dark red indicating higher fertility levels; (b) icon image map: using the legend in Figure 5 to read this image and compare the pattern to that of the IFI image; (c) icon image map using IFI as the background of icon blocks: the color of the icon background is from the IFI pixels, and the foreground bars indicate dynamic icon elements.

soil nutrients at the micro-view level, allowing a user to identify the key factor (or factors) underlying soil fertility in a region. Therefore, it is valuable to apply the icon-based approach to visually analyze soil organic matter and soil nutrients.

5 Concluding remarks

This study innovatively incorporated the icon concept of conventional scientific visualization into the display of multiple GIS raster data to develop an iconmap-based visualization technique. The extension from simple pixels to an icon structure enables each pixel in the simple GIS raster data structure to become capable of displaying multivariate geospatial attributes. This discloses, by way of visual modeling, the geospatial patterns arising from the interaction of several geographically-related variables. Such patterns implicitly exist in the spatial data, and can be uncovered by way of model analysis and visualization. In this sense, geospatial visualization itself provides a mechanism for exploratory analysis. As a case study, the exploratory analysis of soil organic matter and nutrients in Shuangliu County, Sichuan Province, China has been presented in this study, and used to verify the usefulness of the proposed approach. This is the first known attempt at applying the iconmap-based visualization technique for soil fertility analysis. Two types of icon image maps were produced for the visual analysis of soil fertility using both static icon and dynamic icon designs. The results show that the iconmap-based visualization method can better reveal the spatial distribution patterns of soil organic matter, total nitrogen, available nitrogen, available phosphorus and available potassium, providing a basis for the formulized fertilization of soil. Compared with the conventional fused approach for visualizing multivariate geospatial data, the icon image map can provide a consistent visual effect for macro-level views. At the micro-level view, each icon of an icon image map can indicate which icon elements have resulted in the soil fertility condition at a particular site. The shortcoming is that icon image maps are comparatively more difficult to read than conventional maps, as they require a good understanding of the icon templates.

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