Geography, Spatial Data Analysis and Geostatistics. Robert Haining, Ruth Kerry and Margaret Oliver. Geographical Analysis, Vol 42 (1), p.7-31.

This unedited text contains extended details of the literature review of relevant journals and papers. Extracts from this material were included in the journal paper.

(i) Preliminary observations:

Bibliographic databases were searched to evaluate the application of geostatistics in geography compared with its use more generally. We emphasize that the search terms are not exhaustive and will not identify all geostatistical papers in the academic literature in general or within geography, but there might be some informative patterns in the search results to indicate trends. Different databases cover different journals and disciplines and therefore differ in the fields that can be searched. Two databases, Geobase and Web of Science (ISI), were searched for comparison. "GeoBase® is a multidisciplinary database of indexed research literature on the earth sciences, including geology, human and physical geography, environmental sciences, oceanography, geomechanics, alternative energy sources, pollution, waste management and nature conservation. Covering thousands of peer-reviewed journals, trade publications, book series and conference proceedings, GeoBase has the most international coverage of any database in the field" http://www.engineeringvillage.com.erl.lib.byu.edu/controller/servlet/Controller?CID=quickSearch&database=080000. "*Web of Science*® comprises five databases, Social Science Citation Index (SSCI), the Science Citation Index (SCI), the Arts and Humanities Citation Index (A&HCI) databases, Index Chemicus and Current Chemical Reactions." These databases contain information gathered from thousands of scholarly journals, http://images.isiknowledge.com.erl.lib.byu.edu/help/WOS/h_database.html.

The strategy used to search the databases for geostatistical papers was as follows:

Year range: 1990- June 2008
Document type: all
(Geobase) Subject/Title/Abstract includes: krig* OR variogram OR geostat*
(ISI) Title includes: krig* OR variogram OR geostat*

The terms used limit the number of relevant papers identified, but few, if any, non-geostatistical ones would be selected with these terms. The searches produced 4377 and 1596 hits for Geobase and ISI, respectively. There were more hits for Geobase because it scans the abstract as well as the subject for the search terms. Figure 1 shows some of the results from these searches. Mathematical Geology, Figure 1a, has published the most geostatistical papers with twice as many as in Geoderma, the next most popular journal. In a similar study of the geostatistical literature between 1967 and 2005 Zhou et al. (2007), identified the same journals as in Figure 1a as the main publication outlets for geostatistical research, although the order was not exactly the same. The ten most popular journals indicate the main academic areas of geostatistical application: geology, soil science, hydrology, environmental statistics and remote sensing. There is some overlap between these disciplines and physical geography, however, for the Geobase search of institutions publishing more than three papers. Only 9 out of 61 were Geography departments, and this represented only 50 of the over 4000 papers identified by the search. Of these 50 papers, 26 were from the UK (Universities of Edinburgh, Plymouth, Queen's Belfast and Southampton), 7 from mainland Europe (Universities of Trier and Copenhagen) and 8 from the USA (Kent State, Brigham Young and West Virginia Universities). This suggests that the geographical spread of geographers consistently engaged in geostatistical research is quite small. Most other authors who were consistently engaged in geostatistical research were based in geology, agriculture or environmental science departments.

Figure 1b shows that there is a strong positive relation between the number of geostatistics papers identified each year by the two databases (r=0.76). Figures 1c and d show the trend in the number of geostatistical papers found each year in Geobase and ISI, respectively. These show a similar, steady upward trend in the number of geostatistical publications over time. They also identify 1995 and 2000 as having fewer such publications. Geobase identifies 2004 as a bumper year for geostatistical publications, whereas ISI does not. This probably reflects the effect of the Geostatistics Congress, that is held every four years and was held in 2004. Conference proceedings are included in the Geobase search, but not the ISI one.

The Geobase and ISI results were scanned for journal titles that contained Geogra* to determine the number of geostatistical papers published in 'main stream' geography journals. Between 1990 and 2008 only 150 of the 4363 (3.4 %) and 34 of the 1595 (2.1 %) geostatistical papers were published in journals with Geogra* in the title as identified from the Geobase and ISI databases, respectively. Of these papers, in Geobase only 39% of first authors were based in Geography departments. Of the five most prolific first authors of geostatistical papers published in geography journals, only Atkinson, Griffith and Kyriakidis are based in geography departments. Most applications of geostatistics in geography appear to be carried out by, or under the guidance of, a relatively small number of people. There appears to be little general adoption and use of these methods within geography.

The number of geostatistical papers identified in geographical journals each year by the two databases (r=0.47) is less consistent than for all geostatistical papers in a given year (r=0.76. Figure 2b). Figure 2c and d suggests that for both databases the number of geostatistical papers in geography journals has leveled off at about 10 per year for Geobase and 3 per year for ISI. Figure 2a shows that the International Journal of Geographic Information Systems publishes the most geostatistical papers and Geographical Analysis comes second. Both journals are concerned with methodology and there is probably a strong didactic aim on the part of authors to promote geostatistics to a wider audience of geographers. The top ten geography journals for geostatistics are not concerned specifically with human geography, although two of these journals have applications in human geography. Human Geography journals had few geostatistics papers in the period examined; two in *Urban Geography* and one in *Geografiska Annaler Series B Human Geography* which indicates a lack of engagement by human geographers with geostatistical methods. Some of the reasons behind this are discussed in the published paper but others are discussed below.

Many Geographers use the terms 'spatial-' and 'geo-' statistics interchangeably and often do not appreciate the commonalities and differences between the two approaches. This was confirmed by the literature searches. Fifteen to twenty of the 150 geostatistical papers in geography journals that had the term geostatistics in the title, keywords or abstract, treated it as synonymous with spatial statistics or geographic information systems (GIS) and presented no rigorous geostatistical analyses. This confusion of termionology was evident at the 2007 AAG meeting: in the two sessions with geostatistics in the title only 3 of the 10 presentations had any geostatistics. The small number of geostatistics presentations at the meeting (out of a total number ~3000) also indicates the paucity of uptake of these methods amongst geographers. A keyword search using the same terms as for the literature searches above of abstracts for presentations at the 2006, 2007 and 2008 AAG meetings was performed. Of the approximately 3000 papers presented at each meeting, in 2006 there were only 11 geostatistical papers, four of which were concerned with human geography. In 2007 there were 16 papers that engaged with geostatistical methods but only two of these were in human geography. Finally, in 2008 there were 15 geostatistical papers presented at the meeting with only four in human geography.

Part of the problem with the application of geostatistics in human geography relates to very real difficulties with the types of data to be analysed. Can geostatistics be used on area data where polygons are irregular and have different populations? Adaptations of geostatistics that are suitable for application in human geography, for example Oliver et al. (1992; 1998), Goovaerts (2005), Kyriakidis (2004) and Monestiez et al. (2005) are recent and theoretically problematic. Another possible problem is that human geographers often have large datasets that appear to have no need of interpolation, which many geographers tend to equate with geostatistics. However, Oliver et al (2000) show, in the context of remotely sensed and digital elevation data with full cover, that geostatistical analysis has relevance for large sets of data.

Academic genealogy might also be a factor in the lack of uptake of geostatistical methods because it is taught little in Geography departments. Geostatistics is a relatively young discipline and at the time it was expanding into other spatial fields, geographers already had a large set of spatial statistics tools in their repertoire. They often do not recognize geostatistics as a viable, stand-alone subject within spatial statistics and are not acquainted with the many and varied capabilities of the methods. In addition, geostatistical jargon, reflecting the subject's origins in the gold mining industry, can make journal papers inaccessible to the novice in geostatistics who does not know what terms like 'kriging', 'sill' and the 'nugget effect' mean.

Many researchers in geostatistics have modified old Fortran programs and well developed wide-ranging software has been difficult to apply and often expensive to obtain. This has resulted in a major hindrance to the adoption of geostatistics in geography and many other disciplines also. A list of free and commercial software for geostatistical analysis is given at http://www.ai-geostats.org/index.php?id=107, although the list is by no means exhaustive, as important packages such as GenStat (developed at Rothamsted) and Terraseer STIS are not included.

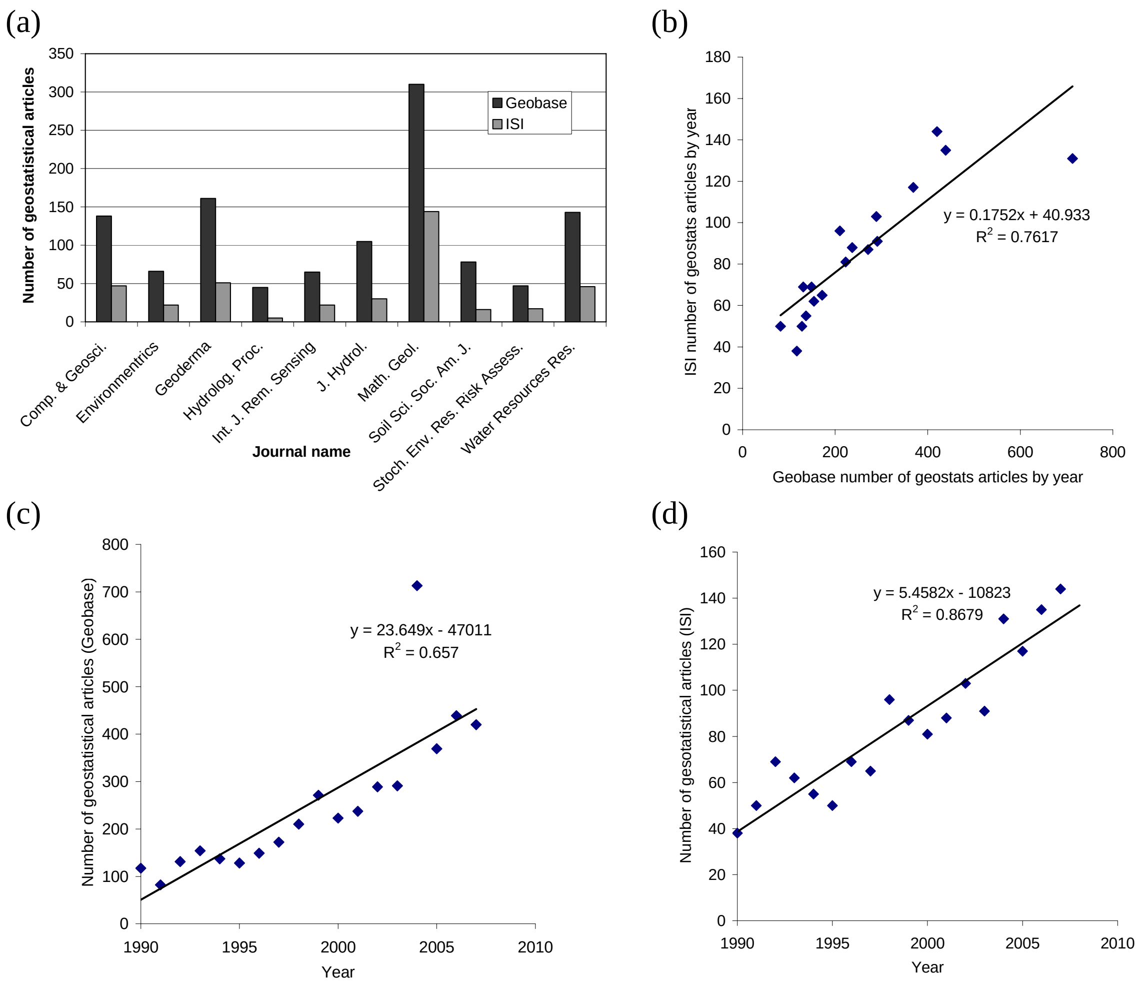

Figure 1. (a) The ten most popular journals for geostatistical papers based on a Geobase and ISI search between 1990 and 2007, (b) relation between number of papers identified in each year by the two databases; relation between the year and the number of geostatistical papers identified by: (c) Geobase and (d) ISI.

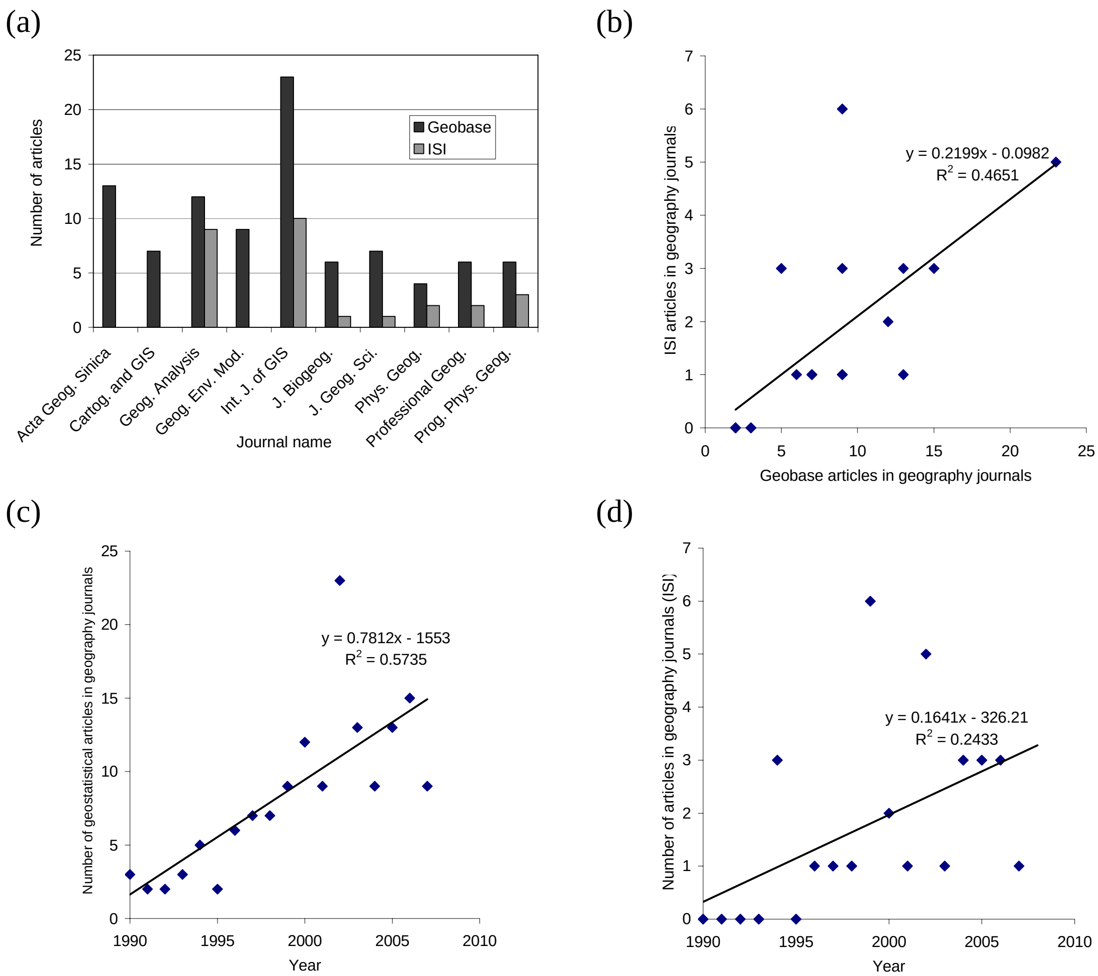

Figure 2. (a) The ten most popular journals with geogra* in the title for geostatistical papers based on a Geobase and ISI search between 1990 and 2007, (b) relation between number of geostatistical papers identified in geography journals each year by the two databases; relation between the year and number of geostatistical papers identified in geography journals by: (c) Geobase and (d) ISI.

(ii) An overview of published papers:

This section is summarized as Table 2 in the published article. Four main sub-fields of the physical world are identified: the atmosphere, hydrosphere, lithosphere and biosphere and from this fourfold division the different branches of physical geography emerge. The majority of physical geography papers in geography journals are concerned with the interpolation of individual variables by kriging. For example, in climatology temperature, rainfall, rainfall erosivity, historic sea level rise, atmospheric deposition of radio-caesium and other pollutants are kriged and mapped (Buzelli et al., 2003; Demidov and Besedin, 2003; Diodato and Russo, 2003; Douguedroit, 2003; Kanaroglou et al., 2002; Lind and Fensholt, 1999; Wright et al., 2002). Kriging has also been applied in landform studies, studies of glacier mass balance and snow storage, elements of the universal soil loss equation, river sediment flux and contamination of lake sediments (Cohen, 2003; Folly, 1997; Jakubek and Forsythe, 2004; Hock and Jensen, 1999; Shutov, 1998). In hydrology, groundwater contamination, groundwater mineralization and hydraulic conductivity of an aquifer have been kriged (Klein, 1992; Li, 2005; Rosenbaum, 2002). Some studies map soil properties (Guo, 2000; Guo, 2001; Kossowski, 1995; Krogh and Fog, 1997; Li, 2004), and in biogeography it was patterns of vegetation including tree lines, species diversity and cave ant distributions (Bio, 2000; Cesaroni; 1997, Rompre, 2007; Strand, 1998). There are only four studies in human geography where kriging is applied for interpolation: the mapping of a rare disease, fertility in India, the incidence of lyme disease and the child sex ratio in India (Webster et al., 1994; Balabdaoui et al., 2001; DeCola, 2002; Guilmoto, 2008, respectively).

Several studies compare kriging with other interpolation methods, such as inverse distance weighting and splines. The majority of these comparisons are for the generation of DEMs from sources including LiDAR and radar (Gao, 1997; Hayakawa, 2007; Lay and Wang, 1996; Lloyd and Atkinson, 2006; Merwin et al., 2002; Meyer, 2004; Reuter et al., 2007; Takahashi et al., 2003; Vilchez and Jose, 2000; Yang and Hodler, 2000). These comparisons corroborate the view that geostatistical methods are viewed by geographers as just another interpolation method.

Apart from its importance for kriging, the variogram has also been recognized as important for interpreting spatial variation. However, the variogram has been generally underexploited, particularly in climatology. In landform studies and hydrology the variogram and correlogram have been used to investigate spatial variation of the permafrost active layer, heavy metals in river sediments, spatio-temporal variability of soil moisture, whilst directional variograms are used to investigate DEM error patterns (Gomersall and Hinkel, 2001; Liu and Jezek, 1999; Wang et al., 2000; Zhang et al., 1999). In biogeography, patterns of diversity in a tropical rain forest, crop yield, tree mortality, plant community boundaries and the spatial rate of change in plant communities have been explored with the variogram (He et al., 1996; Kent et al. 1997; Kent et al. 2006; Li et al., 2002; Meng and Cieszewski, 2006). Variography in human geography studies has been used to: determine the dimensions of industrial growth through population growth, study industrial employment and land use change, examine the spatial structure of towns and cities, relate FDI to city structure and to retrieve industrial complexes from digital images (Bian and Xie, 2004; Esparza, 2004; Ma et al., 2004; Marcinczak and Jakobczyk-Gryszkiewicz, 2006).

More advanced geostatistical methods have received far less attention than kriging and the variogram, but there are examples of incorporating secondary information into the interpolation process. In climatology this takes the form of multiple linear regression kriging of climate variables (Chen et al., 2007), and kriging with varying local means, with external drift and collocated cokriging for estimating air temperature (Hernandez, 2001). In biogeography tick distribution is predicted from climate data (Olwoch et al., 2003), bird diversity and NDVI are cokriged (Lin et al., 2008) and regression kriging is used for predictive vegetation models (Miller, 2005). In soil studies, cokriging is used to improve estimates of soil salt solute in the Yellow River Delta (Wang et al., 2005), imagery and DEMs are used to predict soil organic matter (Broge, 2005) and soil moisture is mapped using passive microwaves (Oldak et al., 2002). Geographers often wish to infer the distribution of one variable from another or use a less expensive variable to improve the prediction of another, but this aspect of geostatistics has been under-used by geographers. Cokriging requires modeling of the coregionalization through cross variograms which provide information on the spatial relations between variables. One study only has made use of this in geography: Pearson and Carrol (1999) examine the influence of spatial scale on cross-taxon congruence patterns and prediction accuracy of species richness. Examples of studies that investigate spatial relations through cross variograms and structural correlations that are not specifically in the geographic literature include those of Atkinson et al. (1994), Carroll and Oliver (2005) and Rawlins et al. (2007). Goovaerts (1997) gives a useful overview of more advanced methods that could be of use to geographers, such as kriging within strata, simple kriging with local means, kriging with external drift, various forms of cokriging and principal components kriging.

Adaptations of kriging, such as binomial cokriging and Poisson kriging have been developed for analyzing counts where the distribution of the data is often highly skewed and the small number problem is an issue. Webster et al. (1994) krige the local risk of a rare disease from a register of diagnoses. The experimental variogram of the frequency was computed with the standard formula and the variogram of the risk was obtained from it by taking into account the number of children at risk and the error associated with each observed frequency. The original work on binomial cokriging by Oliver et al. (1992) was in a medical journal. Poisson kriging was developed for an application in marine biogeography (Monestiez et al. 2005 and 2006). Poisson kriging has since been used in medical geography (Ali et al., 2006; Goovaerts, 2005, 2006a, 2006b; Goovaerts et al. 2007 and Goovaerts and Gereab, 2008), but is suitable for many other types of geographical problems where the small number problem may be an issue such as in the study of crime rates.

Geostatistical change of support received some, albeit limited, attention in the geographical literature as early as 1994. It is related to the modifiable areal unit problem (MAUP) which is of much concern in geography. Mason et al. (1994) studied variable resolution block kriging using a hierarchical spatial data structure, and Bellehumeur and Legendre (1997) investigated tree density and the effect of change of support on sampling. Atkinson and Martin (1999) analysed the kriging of population from census wards to regular grids and compute punctual support variograms, and Atkinson and Tate (2000) reviewed support issues and regularization of the variogram. Gotway and Young (2002, 2005) and Kyriakidis (2004) applied traditional regularization of the variogram so that changes in the support of irregularly sized and shaped areas, as well as regular areas, could be dealt with consistently within a rigorous statistical framework. Kyriakidis (2004) provided a geostatistical framework for area-to-point and area-to-area spatial interpolation, contrasting it with other similar methods to identify its advantages. These Poisson kriging approaches have been combined recently (Goovaerts, 2006a). Area-to-area and area-to-point kriging is a geostatistical development that has come from addressing geographical problems (see Goovaerts, 2008).

Determining the probability of encountering a given class of data that link to specified thresholds, or interpolation of indicator or nominal data can be done with indicator kriging. It is used widely in risk assessments of contaminated sites based on thresholds that define if contamination exceeds acceptable levels (Goovaerts et al. 1997; Brus et al, 2002), together with applications in agriculture (Lark and Ferguson, 2004; Kerry and Oliver, 2007) and for assessing the uncertainty of DEM estimates (Lloyd and Atkinson, 2001). Goovaerts (1997) describes indicator kriging and sequential indicator simulation in detail in his book.

In the Geobase literature search only two applications of indicator kriging were found in geography. Wang (2007) applies the method to estimate pre-settlement vegetation patterns, and Goovaerts (2002a) combines indicator kriging class probabilities with spectral probabilities for the purpose of classifying hyperspectral imagery. Indicator kriging and simulation could be applied in geography where there is a need to deal with nominal or classified data, or the risk associated with exceeding (or falling below) predefined thresholds. Disjunctive kriging is an advanced method of kriging that determines the probability that critical thresholds are exceeded (or not depending on the problem) for risk assessment (Baxter et al. 2006; Gaus et al, 2003; Lark and Bolam, 1997; Lark and Ferguson, 2004; Oliver, 1991; Oliver et al. 1996; Webster and Oliver, 1989; Webster, 1991). There appear to be no applications in the geographical literature, however.

Geostatistics is also of great value in designing sampling schemes for optimal sampling and for kriging (see McBratney and Webster (1981); Atkinson (1991); Brus and De Gruijter (1997); Marchant and Lark (2007) and Odeh et al. (1990)). Only two applications of geostatistics applied to sampling issues were found in the geographical literature. Finley (2007) kriges the likely distribution of contaminants following a bio-terrorism attack and looks at optimal locations for subsequent sampling and Lin et al. (2008) investigate sampling schemes for mapping bird diversity.

In the geographical literature, factorial kriging has been used to filter different scales of variation in remotely sensed imagery so that noise can be discarded and the spatial scale of interest focused on (Warr et al., 2002 and Rodgers and Oliver, 2007). Xu et al. (2000) analyse the spatial distribution of trace elements in the soil of Inner Mongolia by factorial kriging. Goovaerts et al. (2005) applies factorial kriging in health geography to extract information for several variables at different scales and he uses these structural components in correlation analysis to investigate scale dependent relationships with cancer mortality rates. These examples suggest that factorial kriging has considerable potential for wider application in geography.

Storage of remotely sensed image data is important in geography as well as other disciplines, but only one paper applied geostatistics for data compression in the geographical literature (Atkinson et al., 1990). This application of geostatistics has not been widely used; Oliver et al. (2005) describe an application to hyperspectral data at 1 m resolution.

Geographers, particularly those involved in remote sensing and GIS, frequently classify data, however these classifications are based on numerical values and can be spatially incoherent due to noise in the data. Spatial weighting using the variogram can improve the spatial contiguity of classes. Only one application of geostatistics used in this way was found in the geographic literature (see Goovaerts 2002a). Frogbrook and Oliver (2007) (not in a geography journal) give an example of geostatistically weighted spatial classification of soil and ancillary data to identify agricultural management zones. This methodology has received little attention in the wider geostatistical literature, but such regionalization techniques could be exploited by geographers.

Geostatistical simulation of equi-probable spatial distributions provides a means of determining uncertainty in the distribution of values that can be used in risk assessment. Some geographers take an ecological approach to examining human-environment interactions, such as with different forms of environmental pollution, or natural hazards. Six studies involving simulation were found in the geographic literature illustrating how simulation studies have been used. However, all involved prominent figures in the geostatistical community which suggests that simulation methods have not yet received wide acceptance in the geographical community. Dowd and Pardo Iguzquiza (2002) incorporate maximum likelihood variogram uncertainty into geostatistical simulation for use in risk assessment, Bishop et al. (2006) used simulation to assess DEM and soil elevation models for assessing classification accuracy using Sequential Indicator Simulation realizations and quad trees and Gabrosek and Cressie (2002) looked at the effects of location errors on kriging through the use of simulation. Kyriakidis (1999) assessed the accuracy of digital elevation models using simulation and more accurate spot heights and Goovaerts (2002b) illustrated a method of conditioning p-field simulation with a remote sensing application. Two simulation studies in the health geography literature were found. Goovaerts (2005) uses sequential Gaussian simulation to create realizations of cancer mortality rates under increasingly tight conditions and Goovaerts (2006b) uses p-field simulation and poisson kriging to investigate the propagation of uncertainty in cancer mortality risk.

Geographers not only investigate spatial variation, but also temporal variation. Spatio-temporal variograms and space-time kriging can be used to predict phenomena in both space and time. Only two space-time geostatistical studies were found in the geographical literature: Janis and Robeson (2004) use space and time variograms to determine the representativeness of air temperature records, and Su et al. (2003) study the spatio-temporal variation of groundwater salt content. Kyriakidis and Journel (1999) provide a review of geostatistical space-time models.

A final area within the geographical literature are papers of a more theoretical and/or review nature. Diggle and Ribeiro (2002) and Cornford et al (2005) outline Bayesian approaches to geostatistics, the latter being a methodology that can deal with the computational problems of large datasets. Ehlschlaeger (2002), Heuvelink and Burrough (1993), Kyriakidis (2006), Lark (2000) and Oksanen and Sarjakoski (2006) investigate measures of uncertainty and error associated with various estimates. Griffith (1993, 2002) examines links between conditional and spatial autoregressive models and geostatistics, and investigates the merits of combining the two approaches. In these papers he is trying to make links between spatial statistics and geostatistics. Cressie and Helterbrand (1994) provides a review of multivariate approaches to spatial statistical models, Curran and Atkinson (1998) an overview of geostatistical methods for remote sensing and Journel (1996) a review of the use of simulation for modeling uncertainty and spatial dependence. Although not covered in the time period of the present literature search, Oliver et al. (1989a and b) produced a review of geostatistics in physical geography documenting both theory and applications. Oliver and Webster’s (1990) paper suggests the use of kriging as an interpolation method for GIS and Scull et al. (2003) presents a review of predictive soil mapping. The proliferation of reviews introducing new methodology by prominent figures in geostatistics suggests that its methods have not been neglected because of a lack of interest in the field of geography by prominent geostatisticians, rather it seems that these attempts have failed to attract geographers. This may be a result of the lack of practical applications when geostatistical methods are taught and difficulties with software availability.

This review of how geostatistics has been used in geography shows some key trends. Most applications involve kriging as an interpolation method for individual variables and ignore the explanatory power of the variogram. This suggests that many of these studies possibly involve clicking a button that says kriging and using default options that will produce sub-optimal results. Most applications of kriging are in physical geography, particularly climatology and the construction of DEMs. More complex geostatistical methods have been implemented by a few prominent figures, but their use has not spread within the discipline; this might be due to a lack of understanding of such methodologies as well as lack of software to implement such applications. Some key advances that have hindered the use of geostatistical methods in human geography have been made recently and applications of these have been shown mainly in the health geography literature and are being incorporated into user-friendly software. We hope that such advances will improve the uptake of geostatistics by geographers as its methods have the potential to provide answers in many areas of geography, particularly human geography where they have been little used to date.

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