Area (2004) 36.4, 358–366

What kind of quantitative methods for what kind of geography?

Christopher J Keylock* and Danny Dorling**

*Earth and Biosphere Institute and School of Geography, University of Leeds, Woodhouse Lane, Leeds LS2 9JT

Email: c.j.keylock@leeds.ac.uk

**Department of Geography, University of Sheffield, Winter Street, Sheffield S10 2TN

Revised manuscript received 24 June 2004

This paper asks why we teach what we teach to geography undergraduates in quantitative methods courses. We re-consider the origins of quantitative geography and note how partial and historically contingent the traditional syllabus is. From this basis, we suggest that other approaches should be considered in order to provide a broader training in quantitative methods. We then propose an example syllabus that attempts to integrate a range of quantitative methodologies within a common, applied context that is also connected to relevant social, economic and political issues. We conclude that students with a better understanding of methods in physical and social science could be very valuable to the betterment of society, but to achieve this may require a change to our quantitative methods teaching.

Key words: *geographic education, quantitative methods, quantitative revolution, Bayesian statistics, dimensional analysis, undergraduate syllabus*

Introduction

Paradigm shifts often do not require a great many people to be pushing if the conditions are right. In 1964, a quantitative methods study group with an initial membership of six individuals was established in British geography. This had emerged because

> by the early 1960s it became fashionable among the avant-garde to compute correlation coefficients, run 't' tests, and the like. (Harvey 1969, v)

Undergraduate courses such as those developed by Haggett and Chorley at Cambridge (Beckinsale 1997) soon formed the model for introductory courses in data analysis in Britain, while at the same time similar developments were taking place in other countries. It is interesting to note that with respect to physical geography, Gregory stated that

> we are probably on the threshold of yet further change, as there is growing pressure for the incorporation of strictly mathematical, as distinct from statistical, logics into the subject. (Gregory 1976, 388)

If this was the case in 1976, it would seem that the increasing focus upon process understanding in physical geography means that this is even more the case today. Has our methods teaching changed sufficiently to reflect the change in research priorities, the growth in graduate numbers or the skills graduates need since the 1960s?

For some human geographers, the development of a suite of socio-theoretically informed perspectives on geographic issues since the 1960s has meant that quantitative/statistics courses are not only unpopular with students, but might serve a limited function in terms of research training. Such an argument would be considered by others to be symptomatic of a trend in human geography to marginalize the still thriving corpus of work dealing with quantitative analyses of various types (Johnston 2000). Irrespective of one's position on this matter, it would also seem that concerns over the relevance of human geography to policy formation are very real (Martin 2001; Massey 2001; Dorling and Shaw 2002; Lees 2003). Maintaining some basic familiarity with quantitative techniques is likely to help human geography students understand the more empirically oriented literature that is increasingly considered relevant by policy makers. Furthermore, it is stated within the Research Methods programme of the ESRC that

> there is concern that social science research in the UK, however conceptually sophisticated, can lack methodological rigour, in comparison to best research in other European countries or North America. There is also concern that there is an acute shortage of advanced methodological skills among the new generation of social scientists. (ESRC 2003)

Such techniques are likely to be highly valuable for dissertation and other research projects and the QAA (2000, 409) states that 'Within most honours Geography degree programmes, some form of independent research work will be a prerequisite'. Furthermore, maintaining the reputation of geography as a discipline that engages with primary data collection and analysis is essential in the UK if geography is to maintain its part-laboratory subject funding status. Moving beyond academia, successfully being able to demonstrate a basic competence in quantitative methods makes both human and physical geography students more attractive to employers, as well as increasing their knowledge of the world that they will live and work in. Hence, it would seem that quantitative training in one form or another will remain an important part of geographical education.

In this paper, we argue that the quantitative training that many geographers are exposed to is just one particular realization of a range of possibilities and that it is largely based on the ideas introduced to an embryonic quantitative discipline in the 1960s. However, it is by no means certain that it really provides the best possible grounding for today's geographers. If the discipline is to maintain a close connection between undergraduate education and research, a graduating geographer should be as well equipped to commence PhD study in a geography department as a physics or sociology graduate. As research becomes more specialized, we need to ensure that this remains true. After discussing these issues, we propose a quantitative methods course that incorporates a range of methodologies, which embeds these techniques in a series of exercises that lead to the solution of an important applied problem, and which aims to show how quantitative analysis can be complemented by a consideration of social, economic and political factors. An earlier consideration of some of these methods in a degree course, and an appreciation of how different methods complement one another, should improve the understanding of quantitative methods and thus provide the potential to introduce a greater variety of more sophisticated techniques earlier into a degree programme. We conclude by suggesting that revitalizing our quantitative methods training is essential if geography graduates are to compete successfully for PhD places and in the workplace with those graduating from other disciplines.

Quantitative methods in geography traditionally has had an emphasis upon statistical approaches (as opposed to dimensional analysis, optimization or the numerical modelling of equations, for example). Hence, we commence the remainder of this paper with an examination of the statistical component of quantitative methods.

Quantification in geography

Barnes (1998) examined the development of the tools of the quantitative revolution and considered correlation and regression in particular. He discussed the origins of correlation and regression in the work of Francis Galton and their early use in human geography (McCarty 1954) and climatology (Hooker 1907). In physical geography more generally, the adoption of statistical methods occurred much later than in climatology, and at a similar time to human geography (e.g. Strahler 1954; Tobler 1959).

The success of this new geography according to Barnes was due to the manner in which it was able to collapse an initially disparate set of concerns into a single framework (the regression or multiple regression equation). The reduction in emphasis upon such methods in more recent human geography was seen by Barnes to result from the growing awareness that techniques built upon an assumption of statistical independence are not strictly applicable to situations where spatial interdependence is apparent. Furthermore, he also suggested that a growing awareness of the ethically dubious, biometric origins of many of the methods adopted by geographers, such as the links between Galton's work, Eugenics and Nazism, may have also been responsible for this change.

Hepple (1998) considered the move away from quantification to have been more influenced by a change in the types of question that human geographers wished to ask. He noted that Cliff and Ord's (1973) work on spatial autocorrelation (which tackled the issue of spatial interdependence) was published at a time when human geography was moving away from such approaches. Hepple considered the shift away from such work to have occurred when the techniques became too mathematically demanding rather than due to an increased awareness of methodological limitations.

Barnes (1998, 218) cites Gregory (1963) as an early geographical textbook that was 'codfiying the first hesitant forays' into the field of quantitative geography. Gregory goes further in his description of this work when he calls it an 'elementary "cook-book"' (1976, 387) of statistical methods. Subsequently, many introductory texts on statistical methods have been written for geography students (e.g. Taylor 1977; Matthews 1981; Ebdon 1985). However, because many of the textbooks that geographers have been exposed to have this 'cookbook' characteristic, the knowledge of the majority of us is constrained in this manner. Hence, with the exception of a few individuals actively involved in developing and promoting particular methods (e.g. Jones 1991; Brunsdon *et al.* 1996; Fotheringham *et al.* 1998; Jones *et al.* 1998) many of us lack the skills to be able to compare such a technique to alternative methods. Thus, as a discipline, we tend to have a partial and selective knowledge of statistical methods. In fact, one of us gained his statistical training as part of a statistics degree, where almost all of the 'how not to' examples were drawn from the social sciences, including geography.

An alternative statistical framework

The Bayesian view of probability, which dates back to before 1761, is arguably an equally insightful way of expressing probability in geographic research compared to the frequentist approach that is traditionally advocated. None of the six initial advocates of quantitative geography in Britain actively employed Bayesian methods in their research and consequently it is through a historical accident that many geographers are unfamiliar with this approach. With a few notable exceptions, little work has been done by British geographers using such techniques. However, because of the different way of thinking about statistical problems that is imparted using this approach, students who find it hard to understand or be excited about conventional statistics courses may benefit from an exposure to Bayesian methods (Malakoff 1999).

More detail on Bayesian methods is provided in the texts by Leonard and Hsu (1999), Bernardo and Smith (2000) and Congdon (2001). For a geographic perspective on the Bayesian paradigm see Fotheringham *et al.* (2000) and Davies Withers (2002). Relevant examples relating to volcanic eruptions, suicide rates, infant mortality and the prediction of patient flows to hospitals can be found in Solow (2001), Saunderson and Langford (1996), Congdon (2000) and Congdon *et al.* (2001), respectively. In addition, Congdon (2001) provides an introduction to Bayesian approaches to statistical problem-solving using Markov Chain Monte Carlo (MCMC) methods (Gilks *et al.* 1996) and Jackman (2000) considers this method from the perspective of political science. An important advantage of MCMC methods is that they give the full density of parameters rather than assuming normality as is standard in maximum likelihood techniques. Although a formal introduction to Bayesian methods is beyond any introductory programme, we believe that it is worth making students aware that there is a different way of thinking about statistics. After all, at the same time as they are taking a quantitative methods module, students are learning to look at the world around them from different socio-theoretic perspectives. It is important, therefore, that they appreciate that even with numbers there is the possibility of interpreting things in very different ways.

Following from the arguments made above that the knowledge imparted by geographic methods courses is partial, the premise underlying such courses can be opened up for examination and various questions asked. For example: Is there a core to our current methods teaching that should remain for more than just historical reasons? How does our methods teaching relate to contemporary research agendas? In order to develop a quantitative methods course that is relevant, it is worth briefly reviewing the current status of various methodologies in geographic scholarship. In the section below, we offer a personal perspective on this issue.

Quantitative methods in geography

In physical geography, the shift towards process-oriented research, which Gregory identified in 1976, has become increasingly dominant. For example, in geomorphology, detailed studies of processes in the field (e.g. Ferguson *et al.* 1992) are complemented by an increasing number of studies that involve the modelling of the relevant processes (e.g. Lane *et al.* 1999; Hardy *et al.* 2000). However, it would seem that the great proportion of mathematical or modelling studies are undertaken within other disciplines (Rinaldo *et al.* 1993; Howard 1994; Banavar *et al.* 2001) or by people joining geography from other disciplines (Willgoose 1991; Tucker and Whipple 2002). Keylock (2003a) provides some suggestions as to why this may be the case through an examination of the response of different scientific communities to some early papers from the quantitative revolution. British physical geographers perhaps need to ask if they wish to engage with such work directly, or if they would rather be parasitic upon graduates from other disciplines to develop this aspect of geomorphology? One danger of the latter position is that it could result in preventing keen undergraduates from embarking on such topics due to a lack of appropriate methods training. Another subdiscipline to consider in this respect is climatology. Discussion of the ocean–atmospheric system forms an important component of many undergraduate courses on climate change. An important research area in this field involves the use of coupled atmosphere–ocean general circulation models to predict climate change scenarios. In order to be able to effectively examine and critique this literature, students need some appreciation of numerical modelling principles and methods. However, many of those who undertake such research in British geography have an academic background that goes beyond geography (e.g. Valdes 2000; Cai and Luhar 2002). Physical geographers may traditionally have a good grounding in inferential statistics, but in order to engage with contemporary research agendas, improved mathematical and numerical skills would be highly beneficial. However, the teaching of such skills needs to be intimately linked to geographic examples so that students appreciate the relevance of this work.

It would appear to us that for many quantitative methods courses in British geography departments, the actual number of students attending such lectures after the first few weeks is usually dramatically at odds with the number enrolled. This problem emerges because students are simultaneously being taught far more interesting alternative images of the world as compared to the statistical one. Hence, a rather more imaginative approach to this type of teaching is required if such courses are to survive competition from other areas of the discipline. Perhaps a common format is that after descriptive statistics in weeks one and two comes statistical inference, basic hypothesis testing, and then a little regression to end with. In addition, perhaps the lecturer will try to make the census sound interesting as one of us has done with lectures and paper titles that sound increasingly desperate (Dorling 2000 2001 2004; Dorling *et al.* 2001, Dorling and Ward 2003). An alternative is that geographical data analysis is covered in less detail in a course that focuses upon GIS, mapping and visualization. However, universities and the wider world are increasingly awash with people speaking their own peculiar and ever increasingly complex languages. Whether the words are shear stress, disease etiology or cracked gerrymander (Dorling 2002), if students wish to understand the direction environmental science, social medicine or electoral politics (and hence, health and political geography) are taking, they will need to be a little more numerically literate than previous generations of students. The secret to truly understanding the world may well not lie in the realm of numbers, but a very large part of what there is to be understood is now talked about in that realm. If there is any value in still teaching undergraduate students a mixed-up science/social science subject such as geography, it is that this is one of the increasingly few ways of encouraging minds that can think outside the boxes that are currently becoming both more numerous and simultaneously getting smaller and smaller. Hence, a quantitative methods course that can develop these interconnections is of real value.

Introductory geographic methods

So what then could a reformulated introductory, quantitative methods course look like? Of course, it should be plural, introducing the wide range of methodologies used today in geography, and while it should retain an introduction to statistical methods, it should also introduce other approaches, including mathematical methods. However, above all, it should clearly demonstrate to students the relevance of the techniques they are learning and try to make the whole arena of methods teaching rather more attractive. Within some degree programmes it may be the case that BSc and BA methods teaching is delivered separately at an introductory level.

However, it is our impression that many departments, in Britain at least, attempt to integrate first year teaching as much as possible. Hence, the challenge is to produce a programme that is interesting, relevant and challenging for all types of geographer.

In British and American secondary schools over the last 15 years, the emphasis of physical geographic education has shifted from process understanding towards the study of the impacts that environmental phenomena have upon people's lives and livelihoods. Using an example from this part of geography will be familiar to students and naturally allows both human and physical aspects of the problem to be discussed. Furthermore, as natural hazards are a popular area of physical geography, it is proposed that the methods teaching could be oriented around a (probably hypothetical) natural hazard and its impact upon the local population. The example developed below is for the effect of snow avalanches upon a mountain community. However, with a small amount of tweaking it would be possible to adjust this to other problems (e.g. landsliding, river flooding, industrial pollution, the closure of a major employment site). From research into events such as the Aberfan disaster of 1966 (McLean and Johnes 2000) it is apparent that such phenomena involve both physical processes, as well as a suite of political, historical, legal and sociological issues relating to mortality, health and safety, compensation claims and the nature of institutional responsibility.

It is proposed that the first session of the course would include some basic exploratory data analysis (Erickson and Nosanchuk 1979; Cox and Jones 1981) to help the students become familiar with data. They could move on to studying the historical development of the town or region of concern. This would introduce the skills of correlation and regression informally, while also providing the insight that the risk from natural hazards is not static, but changes through time. Using maps, students could determine the extent of the town at particular periods and then relate this to, say, time using various forms of regression. A separate set of data on population through time could also be analysed. In order to give the students familiarity with dimensions and manipulation, they could also be asked to produce a graph of population density through time and determine if density and time are positively or negatively correlated. This example is not strictly correct from an econometric standpoint, but it would be interesting to see if the students can spot why at the end of the session. The advantage of introducing correlation and regression in an informal manner early in a course is that they have a clear visual interpretation and hence are more accessible to students with a limited mathematical background than statements concerning statistical inference.

In the second exercise, these techniques could be revisited with rather more complete datasets that allow the students to gain familiarity with some of the assumptions underpinning regression. A possible case to consider here could be the relationship between the natural hazard under consideration and a climatological parameter such as El Niño or the North Atlantic Oscillation (Keylock 2003b gives one such example for snow avalanches). The assumptions involved in a regression analysis (e.g. normality, normality of residuals, homoscedasticity and insignificant serial correlation of residuals) can be treated graphically using histograms and scatterplots. From this informal understanding, the mechanics of statistical hypothesis testing (e.g. testing the significance of the slope of the regression line, testing for normality, *t*-testing etc.) can then be discussed. Hence, the more abstract concept of statistical inference is introduced after a student has gained a graphical understanding of the concepts, to help bridge the gap in required levels of mathematical reasoning between school and university. Instead of leaping straight into a discussion of probability and significance levels, the idea of a residual can be presented graphically and a histogram compiled from these residuals. It is then possible to derive probabilistic statements from these histograms. Hypothesis testing (e.g. the *t*-test) can then be presented in a graphical manner as an attempt to determine if a normally distributed set of data overlaps sufficiently with a prescribed value or another set of normally distributed data. This can then be considered more formally in terms of the difference in means relative to a distance metric (the standard error or standard error of the difference), the estimator for which is a function of the dispersion (standard deviation) of the data. This approach introduces this material in the opposite order to that usually seen (e.g. Matthews 1981), but in our experience helps students understand what they are trying to achieve because all subsequent discussion can be linked back to initial, visual examples.

The third session could be used to examine the processes that result in the avalanche release. Bivariate relationships between number of avalanche releases and appropriate variables (e.g. temperature, snow depth, three-day total snowfall) could be developed and partial correlation and multivariate analyses hinted at. The strongest relationship found could be combined with an avalanche observer's assessment of the probability of an avalanche release using simple Bayesian decision theory to determine the probability of avalanche release conditioned on this additional information. This introduction to Bayesian decision theory in an applied geographic context should give students experience using conditional probabilities and provide an insight into a different way of thinking about probability. See Dorling (2003) for examples in human geography.

In the fourth session, the run-out properties of the avalanches could be studied and an attempt made to produce a non-dimensional parameter that collapses the dataset of events. For example, Dade and Huppert (1998) suggest that for long run-out rockfalls, the area overrun by the flow (*A*) is a function of the initial potential energy (*PE*) of the flow and the average shear stress (τ):

$$A = k\left(\frac{PE}{\tau}\right)^{\frac{2}{3}} = k\left(\frac{Mgh}{\tau}\right)^{\frac{2}{3}} \qquad (1)$$

where *M* is the flow mass, *h* is the vertical drop, *k* is a dimensionless constant and *g* is gravitational acceleration. Thus, $A/[k(Mgh/\tau)^{2/3}]$ is a dimensionless measure of the deposit, which in terms of the units of length (*L*), time (*T*) and mass is given by:

$$\frac{A}{k(Mgh/\tau)^{\frac{2}{3}}} = \frac{L^2}{([M(LT^{-2})L]/[ML^{-1}T^{-2}])^{\frac{2}{3}}} = \frac{L^2}{([ML^2T^{-2}]/[ML^{-1}T^{-2}])^{\frac{2}{3}}} = \frac{L^2}{(L^3)^{\frac{2}{3}}} = \frac{L^2}{L^2}\text{(dimensionless)} \qquad (2)$$

Thus, using mathematical manipulation of the type introduced at age 15–16, it is possible to show that a whole set of avalanche deposits have the potential to collapse into a single parameter that takes account of the differences in path elevation and avalanche mass. The constant *k* is the ratio of the average width to average length of a deposit (λ) raised to the power of 1/3. Hence, because λ, *h* and *A* can be measured on a map, *M* can be estimated from field surveys of avalanche deposits after the event, and *g* is a constant, with appropriate substitution, equation (1) can be rearranged to give:

$$\tau = \frac{Mgh}{(A/\lambda^{\frac{1}{3}})^{\frac{3}{2}}} \qquad (3)$$

which permits the average shear stress in the flow to be evaluated. The significance of shear stresses for flow dynamics can be emphasized to form connections to more advanced courses in fluvial and glacial processes. Using mathematical techniques to rearrange equations with a physical basis and to analyse dimensions demonstrates to students that mathematics is an important part of geographic scholarship. Furthermore, consideration of dimensions provides an introduction to concepts such as Reynolds, Froude and Richardson numbers, introduced in more advanced courses in fluvial processes or meteorology, and leads to a basic understanding of important issues that underpin environmental numerical modelling, such as the need for high mesh resolutions when simulating high Reynolds number flows.

Having looked at simple demographic and physical geographic aspects of the problem, these can be combined in the fifth session in terms of formal risk analysis (e.g. Keylock *et al.* 1999). Expressing the chance of an avalanche reaching a particular point in the terrain, the chance of a person being there and the chance of death as probabilities allows the risk to be calculated as the product of these terms. Hence, current risk levels can be assessed for particular points in the terrain and future levels can be modelled based on the regression equations developed earlier in the course for town expansion through time and for avalanching and climate change. This exercise will demonstrate how risk analyses combine physical and human geographic processes in a formal manner, while giving students an insight into the nature of probability, and the potential importance of their future studies for dealing with real issues.

In order to bring all this material together, it is suggested that in the final section of the course the medical, political, economic, legal, moral and social implications of events such as avalanches are considered. Undergraduate students as adults are likely to hold positions of power and authority over others in the near future. It would be unethical not to expose them to a knowledge of the potentially adverse effects of decisions that they may make later in life. The risk of an incident (as determined in the previous session) could be discussed with respect to people's perception of this risk and how risk perception alters through time as the memory of a catastrophe recedes. Students could be presented with various management strategies for the avalanche risks with varying economic, political and social consequences and be asked to evaluate which would be preferable. For example, for a town suffering very high avalanche risk, the strategies that could be presented for discussion might include:

1 Evacuating the whole town permanently and resettling the population.
2 Introducing economic incentives to move people away from the region and into a different part of the country.
3 Removing all public buildings (hospitals/schools) to a town nearby where the risk is lower.
4 Undertaking a risk zoning and compulsory or advantageous purchase of all property in high risk zones.
5 Introducing avalanche defences (either in the starting zone or run-out zone) to protect the town, but permanently modify the landscape.

Students would have to balance a consideration of protection of life with the associated societal costs. Thus, at the end of the course, the students would be drawing upon all the knowledge that they have gleaned from quantitative (and other) methods training to begin to solve an important applied problem. Hopefully, this would help students appreciate the way in which quantitative and qualitative methods can complement one another, while providing them with a much more wide-ranging introduction to mathematical and statistical techniques than is commonly the case at present.

Conclusion

An introductory skills module such as that proposed here might serve to increase the range of techniques that geography students are familiar with, while increasing the range of methodologies for dissertations and providing a grounding for more specialized modules later in the degree programme. It has been suggested to us that our idea for an introductory module could be taken further by reflecting upon the need for quantitative methods training more generally, finding out what departments do and then designing a progressive curriculum over two or three years of a degree based on these views. We would certainly support such an idea and would suggest that it would be very beneficial for there to be a national survey undertaken of what quantitative techniques are *actually* taught in geography departments and the skills background of the staff who deliver this material. It would be extremely interesting to know what areas are taught by almost everybody (and to what level of detail), the topics that only a few departments teach and the reasons why they are taught and how these methods are seen as supporting undergraduate and further study. The results of such a survey may be of use to the QAA benchmark committee, would allow an appreciation of the actual state of methods teaching in the UK and could suggest if the additional emphases suggested in this paper are relevant to the training of outstanding geography graduates.

We believe that the introduction to a greater range of statistical and mathematical methods is crucial for producing scientifically competent geography graduates that can compete for jobs and PhD studentships with graduates from other disciplines. At present there is some reason for concern in this area. Imagine you are giving a talk to sixth-form students and afterwards you are approached by somebody who says that they are doing maths, physics and geography at school and thinks they would be really interested in pursuing a career in glaciological research. On the basis of many of the PhD topics advertised in this field recently, and the academic background of a number of our leading researchers in this area, one should not say: 'Great! You should do a geography degree at department *x*', but 'Great! Go and do a physics degree and then join department *x* in three years time'.

Similarly, a student studying economics, sociology and geography and wishing to have a career in area regeneration needs to be sure that a degree in geography is preferable to one in sociology or social policy. The fact that a number of researchers in geography departments would rather recruit people with scientific research skills and add the geography themselves, suggests that we may be disenfranchising our best undergraduates from effective research careers in their chosen discipline relative to those with no experience in this area but a stronger technical background. More importantly, we could be sending out young people into important jobs that they can only pretend they are suitably trained for. If this is true, geography should at least leap forward to where Gregory (1976) thought it should have been nearly 30 years ago and a more rounded quantitative methods training (which makes a significant contribution to a student's overall mark) may be one way of achieving this.

Acknowledgements

Thanks to Adrian Bailey, Peter Congdon, Myles Gould, Niall Johnson, Keith Richards, Greg Tucker and four anonymous referees for their critical comments and their suggestions for references. Of course, the responsibility for the content and the views expressed in this paper rests with ourselves.

References

Banavar J R, Colaiori F, Flammini A, Maritan A and Rinaldo A 2001 Scaling, optimality and landscape evolution *Journal of Statistical Physics* 104 1–48

Barnes T J 1998 A history of regression: actors, networks, machines, and numbers *Environment and Planning A* 30 203–23

Beckinsale R P 1997 Richard J. Chorley: a reformer with a cause in **Stoddart D R** ed *Process and form in geomorphology* Routledge, London 3–12

Bernardo J M and Smith A F M 2000 *Bayesian theory* Wiley, Chichester

Brunsdon C, Fotheringham A S and Charlton M E 1996 Geographically weighted regression: a method for exploring spatial nonstationarity *Geographical Analysis* 28 281–98

Cai X-M and Luhar A K 2002 Fumigation of pollutants in and above the entrainment zone into a growing convective boundary layer: a large eddy simulation *Atmospheric Environment* 36 2997–3008

Cliff A D and Ord J K 1973 *Spatial autocorrelation* Pion, London

Congdon P 2000 A Bayesian approach to prediction using the gravity model, with an application to patient flow modeling *Geographical Analysis* 32 205–24

Congdon P 2001 *Bayesian statistical modelling* Wiley and Sons, Chichester

Congdon P, Campos R M, Curtis S E, Southall H R, Gregory I N and Jones I R 2001 Quantifying and explaining changes in geographical inequality of infant mortality in England and Wales since the 1890s *International Journal of Population Geography* 7 35–51

Cox N J and Jones K 1981 Exploratory data analysis in **Wrigley N and Bennett R J** eds *Quantitative geography: a British view* Routledge, London 135–43

Dade W B and Huppert H E 1998 Long runout rockfalls *Geology* 26 803–6

Davies Withers S 2002 Quantitative methods: Bayesian inference, Bayesian thinking *Progress in Human Geography* 26 553–66

Dorling D 2000 The changing geography of the UK – what only the Census can tell us: the healthy, the unconventional and the spiritual *Burisa* 144 10–15

Dorling D 2001 Anecdote is the singular of data *Environment and Planning A* 33 1335–40

Dorling D 2002 Review of *Bushmanders and bullwinkles. How politicians manipulate electronic maps and census data to win elections* by Mark Monmonier *International Journal of Geographic Information Science* 16 401–3

Dorling D 2003 Using statistics to describe and explore data in **Clifford N J and Valentine G** eds *Key methods in geography* Sage, London 369–82

Dorling D 2004 Happy Valentine's Day: counting and measuring in **Castree N, Sherman D and Rogers A** eds *Questioning geography* Blackwell, Oxford

Dorling D and Shaw M 2002 Geographies of the agenda: public policy, the discipline and its (re)'turns' *Progress in Human Geography* 26 629–41

Dorling D and Ward N 2003 Commentary: Social Science, public policy, and the search for happiness, Editorial *Environment and Planning A* 35

Dorling D, Smith G, Noble M, Wright G, Burrows R, Bradshaw J, Joshi H, Pattie C, Mitchell R, Green A E and McCulloch A 2001 How much does place matter? *Environment and Planning A* 2001 33 1335–69

Ebdon D 1985 *Statistics in geography* 2nd edn Blackwell, Oxford

Erickson B H and Nosanchuk T A 1979 *Understanding data* Open University, Milton Keynes

ESRC 2003 Research methods programme (http://www.esrc.ac.uk/esrccontent/researchfunding/research_methods_programme.asp) Accessed 3 February 2003

Ferguson R I, Ashmore P E, Ashworth P J, Paola C and Prestegaard K L 1992 Measurements in a braided river chute and lobe 1. Flow pattern, sediment transport, and channel change *Water Resources Research* 28 1877–86

Fotheringham A S, Charlton M E and Brunsdon C 1998 Geographically weighted regression: a natural evolution of the expansion method for spatial data analysis *Environment and Planning A* 30 1905–27

Fotheringham A S, Brunsdon C and Charlton M 2000 *Quantitative geography: perspectives on spatial data analysis* Sage, London

Gilks W R, Richardson S and Spieghalter D J 1996 *Markov Chain Monte Carlo in practice* Chapman and Hall/CRC, Boca Raton

Gregory S 1963 *Statistical methods and the geographer* Longman Publishers, Harlow

Gregory S 1976 On geographical myths and statistical fables *Transactions, Institute of British Geographers* 1 385–400

Hardy R J, Bates P D and Anderson M G 2000 Modelling suspended sediment deposition on a fluvial floodplain using a two-dimensional dynamic finite element model *Journal of Hydrology* 229 202–18

Harvey D 1969 *Explanation in geography* Arnold, London

Hepple L 1998 Context, social construction and statistics: regression, social science and human geography *Environment and Planning A* 30 225–34

Hooker R H 1907 Correlation of the weather and crops *Journal of the Royal Statistical Society* 70 1–51

Howard A D 1994 A detachment-limited model of drainage basin evolution *Water Resources Research* 30 2261–85

Jackman S 2000 Estimation and inference via Bayesian simulation: an introduction to Markov Chain Monte Carlo *American Journal of Political Science* 44 375–404

Johnston R J 2000 On disciplinary history and textbooks: or where has spatial analysis gone? *Australian Geographical Studies* 38 125–37

Jones K 1991 Specifying and estimating multilevel models for geographical research *Transactions, Institute of British Geographers* 16 148–59

Jones K, Gould M I and Watt R 1998 Multiple contexts as cross-classified models: the labor vote in the British General Election of 1992 *Geographical Analysis* 30 65–93

Keylock C J 2003a Mark Melton's geomorphology and geography's quantitative revolution *Transactions, Institute of British Geographers* 28 142–57

Keylock C J 2003b The North Atlantic oscillation and snow avalanching in Iceland *Geophysical Research Letters* 30 1254

Keylock C J, McClung D M and Magnusson M M 1999 Avalanche risk mapping by simulation *Journal of Glaciology* 45 303–14

Lane S N, Bradbrook K F, Richards K S, Biron P A and Roy A G 1999 The application of computational fluid dynamics to natural river channels: three-dimensional versus two-dimensional approaches *Geomorphology* 29 1–20

Lees L 2003 Policy (re)turns: gentrification research and urban policy – urban policy and gentrification research *Environment and Planning A* 35 571–4

Leonard T and Hsu J S J 1999 *Bayesian methods: an analysis for statisticians and interdisciplinary researchers* Cambridge University Press, Cambridge

McCarty H H 1954 *McCarty on McCarthy: the spatial distribution of the McCarthy vote, 1952* Department of Geography State University of Iowa, Iowa City

McLean I and Johnes M 2000 *Aberfan: government and disasters* Welsh Academic Press, Cardiff

Malakoff D 1999 Bayes offers a 'new' way to make sense of numbers *Science* 286 1460–4

Martin R L 2001 Geography and public policy: the case of the missing agenda *Progress in Human Geography* 25 189–210

Massey D 2001 Geography on the agenda *Progress in Human Geography* 25 5–17

Matthews J A 1981 *Quantitative and statistical approaches to geography* Pergamon, Oxford

QAA 2000 The Quality Assurance Agency's benchmark statement for geography *Journal of Geography in Higher Education* 24 399–412

Rinaldo A, Rodríguez-Iturbe I, Rigon R, Ijjasz-Vasquez E and Bras R L 1993 Self-organized fractal river networks *Physical Review Letters* 70 822–5

Saunderson T R and Langford I 1996 A study of the geographical distribution of suicide rates in England and Wales, 1989–1992 using empirical Bayes estimates *Social Science and Medicine* 43 489–502

Solow A R 2001 An empirical Bayes analysis of volcanic eruptions *Mathematical Geology* 33 95–102

Strahler A N 1954 Statistical analysis in geomorphic research *Journal of Geology* 62 1–25

Taylor P J 1977 *Quantitative methods in geography: an introduction to spatial analysis* Waveland Press, Prospect Heights, IL

Tobler W R 1959 Automation and cartography *Geographical Review* 49 526–34

Tucker G E and Whipple K X 2002 Topographic outcomes predicted by stream erosion models: sensitivity analysis and intermodel comparison *Journal of Geophysical Research* 107 B9 2179

Valdes P J 2000 South American palaeoclimate model simulations: how reliable are the models? *Journal of Quaternary Science* 15 357–68

Willgoose G, Bras R L and Rodriguez-Iturbe I 1991 A coupled channel network growth and hillslope evolution model 1. Theory *Water Resources Research* 27 1671–84