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Spatial Econometric Issues for Bio-Economic and Land-Use Modelling

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Abstract

We survey the literature on spatial bio-economic and land-use modelling and assess its thematic development. Unobserved site-specific heterogeneity is a feature of almost all the surveyed works, and this feature, it seems, has stimulated significant methodological innovation. In an attempt to improve the suitability with which the prototype incorporates heterogeneity, we consider modelling alternatives and extensions. We discuss solutions and conjecture others.

Keywords: *Bayesian solution; bio-economic land-use modelling; spatial econometrics.*

JEL Classifications: *O18, R15, C11.*

1. Introduction

The objectives of this paper are threefold. First, we survey recent literature using spatial econometric techniques, with emphases on bio-economic and land-use modelling, and provide a brief summary of their relevant contributions (Appendix I, Table A1). Second, in the context of a smorgasbord of archetypical spatial regression models, we highlight thematic developments in the applied literature. Third, we discuss limitations and propose potentially fruitful directions for future research, focussing attentions on one issue that seems particularly problematic in this literature. The starting point for the investigation is the special issue of *Agricultural Economics* (2002). The goal of that special issue was 'to introduce agricultural

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economists to new analytical approaches involving spatial data…' (Nelson, 2002, p. 197). The papers summarised here fall into two basic categories: those that explicitly use spatial econometric methods and those that use geographic information systems (GIS) techniques (broadly defined).

Anselin's (2002) contribution is a review of various issues surrounding the specification and interpretation of spatial regression models, from both theoretical and data-driven viewpoints, and thus serves as a primer on these techniques for the applied econometrician. Topics of discussion include, *inter alia*, the specification of spatial regression models (i.e. 'spatial lag' vs. 'spatial error' and their variants), the choice of spatial weights, and the more exotic topic of spatial latent variable models and the issues surrounding their estimation.

Florax *et al.* (2002, p. 425) define precision agriculture as 'the modern management strategy to cope with soil heterogeneity'. Precision agriculture techniques combine a global positioning system (GPS) and specialised farm machinery to optimally apply fertiliser to potentially improve the efficiency of soil resource use as well as increase profits and lessen the environmental burden. Florax *et al.* (2002, p. 426) note that 'agricultural data exhibit differences depending on the exact location in the field, and spatial patterns or clustering is likely to occur'. Ignoring spatial considerations, as was the practice in previous crop yield studies, can lead to incorrect inferences and poor model performance. Therefore, Florax *et al.* (2002) utilise spatial econometric techniques in their study of millet production on Sahelian coversands in South-West Niger. Their results indicate that there is (1) positive spatial correlation among yield values (their dependent variable) and (2) the spatial lag model outperforms standard OLS estimates of millet yield. Thus, spatial econometric techniques can be utilised to examine issues even in less developed countries where fields are small and technology is lacking.

Swinton (2002) examines the relationship between household poverty and natural resource deprivation using data from 170 households in southern Puno Department, Peru. Under normal circumstances, such data may be expected to exhibit some degree of spatial dependence and thus require the use of formal spatial econometric techniques. However, Swinton (2002, p. 380) posits that 'careful household sampling stratification on the basis of key landscape features can capture important elements of spatial structure' and thus vitiates the need for more formal spatial econometric models. Based on several diagnostic tests that reveal the presence of spatial effects, Swinton (2002) utilises random effects regression techniques in the empirical analysis. Swinton (2002) compares a spatial autoregressive model (using various weight matrices) to ordinary least squares (OLS) with random effects and shows that the results are virtually identical, eliminating the need for the spatial autoregressive model.

Discrete-choice spatial econometric models pose an especially difficult challenge because of the multidimensional nature of the likelihood and corresponding numerical challenges. Building on the work of LeSage (1999, 2000, 2002) and Fleming (2004), Holloway *et al.* (2002) offer a Bayesian alternative that exploits recent developments in Bayesian computation, namely, Markov Chain Monte Carlo (MCMC) techniques that make the resulting econometric model computationally tractable. Holloway *et al.* (2002) apply these methods to an analysis of the 'neighbourhood effects' of adoption of high-yielding variety (HYV) rice amongst Bangladeshi rice producers and find that, indeed, neighbourhood effects are important and that the Bayesian paradigm can offer a solution in these discrete-choice situations.

Several papers in the special issue of *Agricultural Economics* deal directly with spatial issues by using satellite imaging or other GIS techniques to discern changes in land use over time. Nelson and Geoghegan (2002) provide an introduction as to how remotely sensed data are gathered and processed for use in econometric studies, including discussions of geo-referenced data (e.g. raster vs. vector data representations, data formats, etc.), sources of data, and empirical applications of said techniques. Bell and Irwin (2002) describe micro-economic models of land-use change by concentrating on parcel-level land-use changes through time. Their article features descriptions of economic models of land-use change (both theoretical and empirical), data issues (e.g. availability, quality, management and measurement), and an extended discussion of spatial autocorrelation and the concerns involved in the estimation of certain econometric models, such as the spatial probit.

Deforestation is a primary concern of many of the papers and these examples also effectively use spatial techniques to determine factors associated with deforestation. Mertens *et al.* (2002) study deforestation in the Brazilian Amazon, which has been rapidly deforested over the last four decades. Using a logit model and satellite images for 1986, 1992 and 1999 to characterise landscape dynamics, the authors combine spatial techniques and livestock commodity chain studies to provide a spatially explicit methodology to study deforestation in the Brazilian Amazon. Vance and Geoghegan (2002) use a hazard model to determine the effect of various independent factors on the hazard of deforestation among smallholder farmers in southern Mexico. The authors combine both survey data from farm households and the farmer's geo-referenced agricultural plots in the empirical application. Müller and Zeller (2002) investigate the geo-physical, agro-ecological and socio-economic determinants of land-use change in the Central Highlands of Vietnam. Survey data from selected villages, meteorological data and topographical data are combined using GIS software to estimate a multinomial logit model to examine the determinants of land-use change. Monroe *et al.* (2002) examine land-cover change in western Honduras, which has experienced an atypical and significant trend of forest regrowth. Using satellite imagery from 1987, 1991 and 1996, and estimating a series of models, including probit and random-effects probit, the authors find changes in relative prices, infrastructure improvement and topology are related to land-cover change.

The final three papers use spatial techniques to inspect such topics as the uptake decision, site-specific yield response, and the spatial economics of biological control. Staal *et al.* (2002) use a logit model and GIS-derived measures of market access and agro-climate to examine the technology uptake decision of smallholder dairy farms in Kenya. Bullock *et al.* (2002, p. 233) define precision agriculture as 'spatial information technology applied to agriculture'. The authors argue that crop input application recommendations made by extension services have not kept pace with advances in technology. The article summarises research on variable rate input use and show how taking spatial field data into account *via* variable rate farming can make farming more profitable. Nordblom *et al.* (2002) study the effect of the release of crown weevil that specifically target Paterson's curse and other weeds in southern Australia using data for 31 districts. Their analysis tries to discern whether additional releases of crown weevil are justified (in a cost–benefit framework) to control the various weed species.

2. Spatial Regression Models of Reference

By and large, the spatial-econometric contributions in that special issue generate inferences in the context of a prototypical regression framework, which we represent symbolically as

$$\begin{aligned} \mathbf{z} &= \rho\mathbf{W}\mathbf{z} + \mathbf{X}\boldsymbol{\beta} + \boldsymbol{\upsilon}, \\ \boldsymbol{\upsilon} &= \lambda\mathbf{W} + \boldsymbol{\varepsilon}, \\ \boldsymbol{\varepsilon} &\sim f^{\mathrm{MN}}(\boldsymbol{\varepsilon}|0, \sigma^2\mathbf{I_N}), \end{aligned} \tag{1}$$

where $\mathbf{z} \equiv (z_1, z_2, \ldots, z_N)'$ denotes an N-vector of responses of interest; ρ depicts correlation across the responses; $\mathbf{W}$ denotes an N-dimensional spatial weight matrix; $\mathbf{X} \equiv (\mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_N)'$, $\mathbf{x}_1 \equiv (x_{11}, x_{12}, \ldots, x_{1K})'$, $\mathbf{x}_2 \equiv (x_{21}, x_{22}, \ldots, x_{2K})'$, …, $\mathbf{x}_N \equiv (x_{N1}, x_{N2}, \ldots, x_{NK})'$ denotes observations on the covariates; $\beta \equiv (\beta_1, \beta_2, \ldots, \beta_K)'$ denotes the corresponding K-vector of response coefficients; $\upsilon \equiv (\upsilon_1, \upsilon_2, \ldots, \upsilon_N)'$ denotes an N-vector of random disturbances; λ depicts correlation across the disturbances; $\varepsilon \equiv (\varepsilon_1, \varepsilon_2, \ldots, \varepsilon_N)'$ denotes another N-vector of random disturbances; and $f^{\mathrm{MN}}(\varepsilon|\mathbf{0_N}, \sigma^2\mathbf{I_N})$ denotes the multivariate normal probability distribution function defined over the vector ε, with mean $\mathbf{0_N}$ and covariance $\sigma^2\mathbf{I_N}$. In some contexts, the response variable $\mathbf{z}$ will be observed, in which case $\mathbf{z} \equiv \mathbf{y} \equiv (y_1, y_2, \ldots, y_N)'$, an N-vector of observable quantities. In other contexts $\mathbf{z}$ will be latent and will relate in some way to the observed data $\mathbf{y}$. In either case, one feature of the setup in (1) that is fundamental to the analysis is that the indices defining the subunits in question, $\{i\}_{i=1}^N$, contain spatial information. The investigator observes data $\mathbf{X}$, $\mathbf{W}$ and $\mathbf{y}$ and makes inferences about the unobserved parameters $\theta \equiv (\beta',\rho,\lambda,\sigma)'$. The majority of the papers that we surveyed employ particular specialisations of the setup in (1) and it is useful to present it as a point of reference. For example, Holloway *et al.* (2002) observe adoption behaviour among Bangladeshi rice producers using farm-level data. Parameter λ is constrained *a priori* to equal 0; parameter σ is constrained to equal 1; the observed $\mathbf{y} \equiv (y_1, y_2, \ldots, y_N)'$ are binary values, equalling 1 if the farmer adopted HYV rice technology and equalling 0 otherwise; and the elements of $\mathbf{z}$ are latent responses constrained to be non-negative if adoption occurs and constrained to be negative otherwise.

Formally, if $\lambda = 0$ we have what is referred to as a spatial autoregressive, or SAR model. Likewise, if we constrain $\rho = 0$, we have what is commonly referred to as the spatial error, or SEM model. If both spatial parameters are allowed to enter the estimating equation, we have what is referred to as the general spatial model, or SAC model. For convenience, we utilise these terms in the following sections.

Early work with spatial regression commenced with Cliff and Ord (1975). The methodological literature has witnessed many advances since then, with important collections of these advances in Anselin (1988), Anselin (1999), Anselin (2003) and LeSage (2002).

3. Environmental Resources, Forestry and Conservation

An early application of spatial regression techniques in ecology is Pinel-Alloul *et al.* (1988), who examine the effects of body size, depth and sampling scale on the spatial heterogeneity of zooplankton in Lake Cromwell, Quebec, Canada. The importance of incorporating spatial information into statistical analyses of conservation biology is a recurrent theme in the literature re-emphasised by Carroll and Pearson (2000). Modern methodological advances, especially the Gibbs sampler and the advent of more general MCMC methods, permit Hertzberg *et al.* (2000) to study the effects of spatial habitat configuration on recruitment growth and population structure of arctic Collembola. Their Bayesian methodology employs a finite-mixture distribution (Lavine and West, 1992; Diebolt and Robert, 1994) to model heterogeneity in densities of the subject matter. Dennis *et al.* (2002) employ the novel Getis–Ord (Getis and Ord, 1992) distance-statistic method to calculate the smallest distance to ensure that each sample point of upland beetles has at least one neighbour and make inferences about how patterns of habitat heterogeneity affect the distribution of representative ground and rove beetles sampled at an upland site of varied landform. The complex spatial heterogeneity of ecological systems is a common theme in the respective applications of Newbold and Eadie (2004), Polasky *et al.* (2005) and Shi *et al.* (2006). These contributions are also linked by their overriding theme that is 'predicting the probability of persistence of a species given a land-use pattern' (Polasky *et al.*, 2005). Claessens *et al.* (2006) investigate the problem of incorporating spatial autocorrelation among a sample of kauri using logistic regression. They discover thresholds as significant in explaining the age distribution and the geographic dispersion and ecology of the species in the Waitakere ranges of New Zealand. Laband and Nieswiadomy (2006) use the SAR model to examine the impact of environmental and political factors affecting the risk of extinction of species in 49 US states. Finally, two contributions to the conservation literature deserving special mention are Newburn *et al.* (2006) and McPherson and Nieswiadomy (2005). In the former the SEM model is used to derive inferences about targeting strategies for land conservation in the presence of heterogeneous land costs and heterogeneous probabilities of land-use conversion. In the latter, the SAR model is applied on a global scale to measure the (Grossman and Krueger, 1995) conjecture of a Kuznets-type (approximately U-shaped) relationship between threatened bird and mammal species and the level of per-capita income in 113 countries at various stages of development. They find that significant spatial autocorrelation exists, with shocks spilling over, geographically, into neighbouring countries.

Heterogeneity is, again, an overriding theme in the conservation literature focused on genetic resources. Early work that is noteworthy for its methodological contributions are Epperson (1990) and Epperson (1993), both of which focus on the geographic distribution of genetic variation in plants. In the former a SAR model is used and in the latter a STAR (space-time autoregressive) model is employed. In Bjørnstad *et al.* (1995) population genetic drift and genetic mappings are assessed taking explicit account of the fact that both the genetic makeup and the environmental conditions of a population are spatially correlated. And in He *et al.* (2006) spatial autocorrelation of genetic variation in a rainforest endangered perennial is assessed.

Contributions related to forestry can be broadly classified into two categories: those that employ a spatial regression model as the main focus of the work (Köhlin and Parks, 2001; Pattanayak and Butry, 2005; Mena *et al.*, 2006) and those works (Roberts *et al.*, 2000; Kohlin and Parks, 2001) in which the spatial regression is ancillary. The target focus is reducing rates of fragmentation and deforestation of naturally forested areas. Frequently, the deforestation rate is the observed dependent variable.

Kerr *et al*. (2003) employ classical and Bayesian spatial regression techniques to make predictions of land use and carbon storage on a large geographic and temporal scale. On a smaller scale, spatial correlation among heavy-metal contaminated soil sites is at issue in Schnabel and Tieje (2003). Kim *et al*. (2003) improve the methodology for estimating hedonic price functions in the presence of spatial dependence. They apply a spatial-hedonic housing-price model to the Seoul metropolitan area and measure the marginal value of improvements in concentrations of sulphur dioxide and nitrogen dioxide. Diagnostics suggest that the SAR model, rather than the SEM model, is preferred. Finally, an innovative methodology combing both the spatial lag and spatial error components (the SAC model, as in equation (1)) is presented in Atasoy *et al*. (2006). Using panel data they relate the density of residential development and the change in residential land use to three measures of water quality.

Deserving special attention is the contribution by Assunção (2003), which develops innovative alternatives to the traditional framework in equation (1). At issue is the notion that regression covariate coefficients may vary as they would in a traditional random-coefficients framework (Hildreth and Houck, 1968), with two peculiarities. First, the variation arises in response to variation in space. Second, the differences across regions is not discrete but, rather, varies smoothly as a function of the area location. The model is implemented using Gibbs and Metropolis–Hastings sampling and is highlighted in applications to the adoption of new technologies by Brazilian farmers, the diffusion of a zoonotic disease in Bel Horizonte, a large Brazilian metropolitan area and the study of women's fertility statuses in Minas Gerais, a Brazilian state.

Huang and Cressie propose a Kalman-filter-based approach for estimation and prediction in the context of 'snow-water-equivalent' data and apply it to predict water availability in the Animas River basin in southwest Colorado. Additional works employing explicitly spatial statistical techniques are available from the survey articles by Vaughan (1994), Bateman *et al*. (2002), Nilsson *et al*. (2003) and Batabyal and Nijkamp (2004).

4. Marine Resources

Recent contributions in this category were given impetus by the commissioning of a special issue devoted to spatial modelling in fisheries economics. The works presented there (Holland *et al*., 2004; Wilen, 2004; Holland, 2004; Sanchirico, 2004; Dalton and Ralston, 2004; Smith and Wilen, 2004; Hicks *et al*., 2004; Curtis and McConnell, 2004; Strand, 2004) cover an eclectic range of issues, all related in some way to the spatial organisation of marine resources. Topics include making use of increasingly abundant spatial information to enhance the efficiency of management of coastal fisheries, designing cost-effective marine reserves, analysing the effects of spatial closures in a fishery, enhancing realism in bio-economic models by endogenising port choice, assessing the welfare losses arising from spatial set asides, modelling fishermen's spatial decisions and comparing estimates of fishermen's risk preferences between spatially aggregated and spatially disaggregated models. Five of the nine papers appearing in the issue are inherently empirical, with formal econometric procedures being applied. Surprisingly, formal spatial econometric modelling of the type espoused in equation (1) is absent.

Another collection of papers devoted to the topic Spatial Models in Fisheries Economics contains four papers devoted to the topic of developing formally spatial econometric models of fisheries. Mistiaen and Strand (2000) develop and test a short-run, expected-utility maximising model of fishermen's location choices. Using the random-parameters logit model in their empirics, they are able to incorporate heterogeneity in risk preferences across subunits of the sample. Curtis and Hicks (2000) investigate the cost of area closures mandated by regulations designed to conserve sea turtle populations. Their empirical application is the Hawaiian pelagic longline fishery and they implement their site-choice analysis using the logit specification. Smith (2000) discusses aspects of modelling information processing by fishermen, including the choice between structural and reduced-form models, decay in information transmission during search and complexities encountered in modelling spatial search and information sharing. Fleming (2000) emphasises the significance of spatial heterogeneity in fisheries and compares the utility of discrete-choice models of fishermen's site preferences with alternative techniques. Once again, formal spatial econometric models of the type engendered in equation (1) are absent.

Of the remaining papers surveyed in this category, two (Sanchirico and Wilen, 2005; Sanchirico, 2005) are conceptual. Broadly speaking, they relate to the spatial management of renewable resources in general and the management of marine reserves in particular. In contrast, an additional two works are empirical and are deserving special attention. Smith (2002) presents two econometric approaches for predicting the spatial behaviour of renewable resource harvesters and assesses empirically the spatial patterns of exploitation in the California sea urchin fishery. At issue is the desire to understand how the magnitude and the spatial distribution of fishing effort respond to biological, economic and oceanographic factors. Two models are investigated. One, which is macro in nature, combines count-data and seemingly unrelated regression techniques; the alternative model, which is micro in orientation, employs discrete-choice techniques to model fishermen's site preferences. The macro-model, by its very structure, incorporates correlation across space; the micro-model, a nested-logit regression, does not. Significantly, in the context of present attentions, the former 'outperforms' the latter (Smith, 2002, p. 524).

Finally, in this section, Su *et al.* (2004) present an innovative methodology for modelling stock recruitment of pink salmon in the north-east Pacific ocean. Specifically, they model the number of adult recruits produced per spawner (the survival rate) from a specific stock in a given brood year. Their objective is to improve the understanding of the effects of environmental factors on spawner-to-recruit survival rates. For this purpose they construct alternative spatial hierarchical Bayesian models and compare them. Hierarchical modelling, which has its roots in the early work of Lindley and Smith (1972) and is now commonplace in many fields, has, perhaps, enjoyed less frequent application in the bio-economic and agricultural-economic fields. We conjecture that the Bayesian hierarchical methodology offers enormous scope for enhancing the dexterity with which our current portfolio of techniques is usefully applied to model heterogeneity in spatial analyses. In this regard, one important contribution of Su *et al.* (2004) is the introduction of distance-based, spatially correlated prior distributions for stock-specific parameters. Significantly, they find that the spatial hierarchical Bayesian methodology produces more consistent and precise estimates of the effects of sea surface temperature on productivity than does a conventional single-stock approach.

5. Agricultural Resources and the Land

More than other categories, agricultural-resource and land studies witness the most intensive use of the prototypical spatial econometric structures. Examples include studies of the spatial organisation of commodities (see, for example, Roe *et al.*, 2002; Isik, 2004), in which the SAR model is employed, as well as studies of spatial relationships between commodity prices (see, for example, Florkowski and Sarmiento, 2005), in which the spatial error (SEM) model sees frequent employment. Beyond the studies examining the geographic makeup of industry, two collections dominate this group, namely studies examining crop yield and studies examining land use. Each of eight studies surveyed relating generally to spatial yield prediction (Voortman *et al.*, 2004; Anselin *et al.*, 2004; Lambert and Lowenberg-DeBoer, 2004; Dark, 2004; Persson *et al.*, 2005; Miller, 2005; Wang *et al.*, 2005) contain explicit use of one, and in most cases two, of the prototypes in equation (1). A general theme emerges. This theme is improving inferences about yield and crop response to inputs while permitting site-specific heterogeneity.

Irwin and Geoghegan (2001) survey the literature in spatially explicit land-use change prior to 2000 and Parker *et al.* (2003) survey the literature on multi-agent-system models of land-use change. In contrast to the crop-yield studies, many studies of land use and land-use change use methods alternative to those in the standard spatial frameworks. Pelkey *et al.* (2000) consider vegetation change in Tanzania using a large-data sample that prohibits inversion of an N-by-N matrix required to implement the Gibbs sampler. Nelson *et al.* (2004) study infrastructural congestion and deforestation using multinomial-, nested- and random-parameters logit techniques that preclude spatial-weights matrices. Cho and Newman (2005) extend a two-stage discrete-choice modelling procedure (Bockstael and Bell, 1998) to permit estimation of land development densities. Robertson *et al.* (2006) use spatial regression tree analysis to reference water quality within streams. Müller and Zeller (2002) use multinomial logit techniques to study land-use dynamics in Vietnam. The remaining articles we surveyed in the land-use category (Walker and Solecki, 1999; Crocker and D'Souza, 2002; Munroe *et al.*, 2004; and Polsky, 2004) exemplify the versatility of the SAR and SEM frameworks in a wide and broader set of circumstances, including studies of the relationship between climate change and land-use classification change in the central and eastern USA and in Western Honduras. Liu *et al.* (2006) consider the stability of site-specific yield responses over time. Finally, within this category, Verburg *et al.* (2004) survey methodologies employed in land-use change studies. In assessing progress and looking to the future they propose development of models that 'better address the multi-scale characteristics of the land use system, implement new techniques to identify neighbourhood effects, explicitly deal with temporal dynamics and achieve a higher level of integration between disciplinary approaches and between models studying urban and rural land-use change' (p. 309).

Other papers in this general category provide further examples of the SAR and SEM models unifying the mathematical foundations of regional science (Griffith, 1999), better implementing integrated regional econometric and input–output modelling (Rey, 2000), improving understanding of farmland values decomposition (Plantinga *et al.*, 2002; Huang *et al.*, 2006) and better understanding the drivers of change in the relationship between environmental amenities and human settlement patterns in the rural–urban fringe in the midwestern USA (Gustafson *et al.*, 2005).

In closing this section, it is relevant to comment on the use of discrete-choice technologies used extensively in location-choice studies. Without exception the surveyed works employ classical procedures. They rely almost exclusively on variations of logit methodology. This possibly arises due to computational problems encountered in classical estimation of the multinomial probit. However, the logit methodology suffers a significant disadvantage because it prohibits explicit spatial regression analysis. Such is not the case with probit estimation, and incorporation of explicit spatial weight matrices and associated correlation parameters follows naturally from the binary- or multinomial-probit specifications. Bayesian estimation of multinomial probit models and comparisons with classical methodology are reviewed in Geweke *et al.* (1994).

6. Public Choice Toward the Environment, the Land and Agricultural Trade

Johnston *et al.* (2002) examine whether survey respondents react to spatial factors in stated preference surveys and the ways in which spatial interaction may influence welfare measures. Portnov (2005) examines development similarities in urban clusters using both traditional ordinary least squares (OLS) and spatial econometric (SAR model) techniques. Bode (2004) employs spatial econometric techniques to model interregional knowledge spillovers between West German planning regions in the 1990s. Carrington (2003) studies regional European economic growth utilising the SAC model, that is, one that includes both spatial lag and spatial error terms. Babcock *et al.* (2005) look at wage spillovers in public-sector teacher negotiations using panel data and spatial econometric techniques. Ertur *et al.* (2006) model both spatial heterogeneity and spatial dependence in the estimation of the convergence of European regions over the 1985 to 1995 period. Bivand and Szymanski (1997) develop a model of yardstick competition and show how spatial dependence can manifest itself in the form of externalities in contract negotiation between agents. The theory is tested with data on garbage collection in the UK using spatial econometric techniques. Buzzelli *et al.* (2003) study the effect that spatio-temporal changes in air pollution levels change with socioeconomic status. Dietz (2002) reviews both the theoretical and empirical literature on neighbourhood effects in the economic, sociological and geographical literature. Immergluck (1999) utilises spatial econometric techniques to study changes in commercial building activity in Chicago in the 1980s. Mobley (2003) is the first paper in the health economics literature to use spatial econometric techniques to model hospital market pricing. Porojon (2001) reformulates the popular gravity model of trade using spatial econometric techniques and illustrates the technique with data from the EU. Murdoch *et al.* (2003) considers treaty participation as a two-stage game and apply a spatial probit to the Helsinki Protocol.

7. Housing, the Economics of Real Estate and the Rural-Urban Fringe

The economic analysis of housing markets provides ample opportunity for spatial statistics and other GIS-related techniques to be utilised for inference. Pace and LeSage (2004) edited a special issue of the *Journal of Real Estate Finance and Economics* devoted to spatial statistics and real estate. Gelfand *et al.* (2004) present a class of spatio-temporal models of housing prices that models the movement of these prices over time. They find that the spatial component is very important in explaining house prices. Case *et al.* (2004) cleverly employ a competition on modelling spatial and temporal components of house price for anyone wishing to join. The results indicate the importance of spatial considerations in housing prices. Militino *et al.* (2004) use data from 293 properties in Pamplona, Spain and several spatial statistical techniques (e.g. lattice models and kriging) to analyse the behaviour of the market prices of used dwellings. Brasington (2004) posits a model of two internally homogeneous communities jointly providing a public good, in this particular case, education. The author then empirically estimates the effect of the loss of control over the public good on housing prices using spatial econometric techniques. LeSage and Pace (2004) develop a model for spatially dependent missing data and using actual data on sold as well as unsold properties, to empirically show that their methods improve prediction.

The use of spatial statistics in real estate is becoming increasingly popular and reviews of techniques and application can help further popularise these methods. Páez and Scott (2004) show the connection between urban analysis and spatial statistics by reviewing developments in spatial statistics and then presenting applications. Pace and Le Sage (2004) provide an overview of spatial statistical techniques (including spatial regression and kriging) as well as some relevant literature and software options for practitioners. Pace *et al.* (2000) compare and contrast alternative real estate models that explicitly incorporate spatial correlation.

Empirical applications of spatial statistics cover many different aspects of land use. Hardie *et al.* (2001) develop a theoretical model of real estate values in terms of both agricultural returns and potential non-farm value. Their model also explicitly incorporates the rural–urban fringe by placing all new housing construction at this boundary. The empirical analysis accounts for spatially correlated errors and incorporates panel data methods as well. The results indicate that farm earnings and non-farm factors play a role in farmland prices. Thibodeau (2003) examines three issues related to hedonic housing price models: one, the procedure used to identify housing submarket boundaries, two, the econometric techniques used in estimation; and three, the characteristics of the local housing market. The work of van der Kruk (2001) studies the economic impacts of Dutch wetlands amenities. A new spatial model termed the SARMA(d) is illustrated and used in the empirical analysis. Boxall *et al.* (2005) use data from Central Alberta, Canada and a SEM model to study the effects of oil and gas facilities on rural residential property values. Colwell and Munneke (2003) estimate the land price gradient with respect to distance from the city centre using piecewise parabolic multiple regression. The findings support the idea of falling land prices with distance. Ding (2001) combines GIS and spatial econometric techniques to study land development patterns. Entwistle *et al.* (2005) use spatial regression techniques to show that population density negatively affects, but population growth positively affects, the area devoted to upland crop production in Nang Rong district, Thailand. Lima and Macedo (1999) consider endogenising the spatial weights matrix in a housing-market study in Brazil. Morenhoff (2003) considers birth-weight effects in a large cross-section of Chicagoan suburbs. Talen assesses land-use zoning restrictions in relation to human diversity (2005). Bin *et al.* (2006) develop a spatial hedonic pricing model to measure willingness to pay in amenities-and-risks correlated coastal housing markets, and Kestens *et al.* (2006) assess hedonic-pricing heterogeneity across household types. Finally, Brasington and Haurin (2006) and Brasington and Sarama (2007) estimate, respectively, a spatially lagged house-price hedonic model and a spatially correlated hedonic Bayesian probit model.

8. Thematic Developments and Extensions

Finally, because our major emphasis resides in the Bayesian approach to processing spatial data, we make brief mention of a landmark text that provides the Bayesian alternative to the classical likelihood-based text by Cressie (1993). Banerjee *et al.* (2004) present a comprehensive treatment of Bayesian hierarchical modelling of spatial data and review many recent and forthcoming contributions including applications to real estate (Gelfand *et al.*, 2004, 2007), meteorological processes (Handock and Wallis, 1994; Sansó and Guenni, 1999; Wikle *et al.*, 2001; Diggle and Ribeiro, 2002), the environment and natural resources (Brown *et al.*, 1994; Best *et al.*, 2000; Fuentes, 2001; Zhu *et al.*, 2003; Huerta *et al.*, 2004; Agarwal *et al.*, 2005) and human development (Müller *et al.*, 2001). Together these applications provide a rich array showcasing the full power of the Bayesian hierarchical approach to spatial data.

Because spatial econometric modelling in the bio-economic and land-use categories is so eclectic, it is only with difficulty that thematic developments emerge. Yet some fairly clear orientations are apparent. Broadly described, an overarching theme in this diverse literature appears to be loosening the constraints of our prototype models in order to engender added realism to the modelling environment. In this way research aims to close the gap between the realities of the data-generating environment and the modelling context the research employs to depict it. 'Heterogeneity' is ever present. It overarches and underpins each of the literary divisions we have chosen. For example, in the contexts of forming site-specific yield predictions (as in Voortman *et al.* (2004) and in Anselin *et al.* (2004)), utilising satellite imagery of the Ngorogoro crater (as in Pelkey *et al.*, 2000) or mapping appropriate covariates to conservation biology measures (Claessens *et al.*, 2006; Shi *et al.*, 2006), the researcher confronts the problem of better incorporating heterogeneous, site-specific factors that have a fundamental impact on the biological and natural resource process. In Anselin *et al.* (2004) heterogeneity arrives in the form of the unobserved nutrient status of a yield site; in Pelkey *et al.* (2000) it is present in the unobserved behaviour of predatory mammals and migratory species; and in Shi *et al.* (2006) it arises due to the unobserved complex spatial heterogeneity of ecological systems. In each case heterogeneity is fundamental to the data-generating environment. In this context it is not surprising that many of the innovative developments in spatial model methodology arise as direct responses to the desire and the need to better incorporate heterogeneity in the biological, agricultural or land-use process. Therefore, in suggesting extensions and potentially fruitful directions for new research we focus attention on heterogeneity in the modelling of bio-economic and land-use resources.

Several directions identify themselves from the innovative methodologies in Assunção (2003) and Su *et al.* (2004). These studies make efficient use of the Bayesian hierarchical methodology. Hierarchical modelling of processes to adequately represent heterogeneity is common in Bayesian inference. Koop and Tobias (2004), for example, illustrate the methodology's advantages in the context of modelling returns to schooling. Tsionas (2002) proposes a stochastic frontier model with random coefficients to separate technical inefficiency from technological differences across firms and to free the frontier model from the restrictive assumption that all firms must share exactly the same technological possibilities. Smith and LeSage (2004) develop a Bayesian spatial prohibit with individual random effects and Kamarianakis (2006) considers hierarchical modelling for spatial time series as an alternative to spatial seemingly unrelated regressions estimation. Other examples can be found in the literature, particularly in the medical sciences. In the context of our prototypical models in equation (1), a natural question that arises is the modification required in order to incorporate heterogeneity in the bio-economic and land-use process. Where it is observable among covariates we are able to condition inferences by simply including the relevant covariate information in the econometric exercise. This point is important. It is only unobserved heterogeneity with which we are concerned. Unobserved, heterogeneous factors that impact the modelling environment may be present in any of the parameters about which we make inferences. Thus, heterogeneity may impact the regression coefficients, β, or the sampling standard error, σ. However, because it delimits so many methodological differences over a standard regression framework, in the space that remains we focus attentions only on the spatial weights matrix, $\mathbf{W}$, and the parameter depicting correlation among contiguous geographic units, ρ. Durlauf (2004) surveys the settings in which phenomena give rise to spatial dependence, termed 'neighbourhood effects'. Many of the settings he surveys differ markedly from the one depicted in equation (1), which is a homogeneous set of correlations between contiguous regions within the sample. The many assumptions embedded in this overly simplistic framework beg some obvious questions. The hierarchical extension of the basic spatial relationship posits a distributional assumption across subsets of the sample, say, $i = 1, 2, \ldots, N$, concomitantly replacing '$\rho\mathbf{W}$' in equation (1) with alternative assumptions '$\rho_1\mathbf{W}_1$', '$\rho_2\mathbf{W}_2$', … ,'$\rho_N\mathbf{W}_N$' across subsets and assuming, simultaneously, that $\rho_1, \rho_2, \ldots, \rho_N$ are linked as draws from some common distribution, $f(\rho_1, \rho_2, \ldots, \rho_N|\rho)$ with 'ρ' the overarching 'hyperparameter' depicting correlation across the complete sample. However, alternatives exist.

A first question about the relationship '$\rho\mathbf{W}$' is the magnitude of the geographic space within which dependence exists. When there is good reason to question the size, but not the pattern, of contiguity in the sample, it is natural to combine contiguous regions forming successively larger neighbourhoods in which spatial dependence might exist. Subsequently, one can test for the neighbourhood size that is most appropriate among the alternatives. Holloway and Lapar (2007) implement this modification to a model of northern Philippino smallholders and determine that, across the twelve geographic units comprising the sample, a significant, positive, neighbourhood effect exists and that it spans a three-unit radius. Despite its attractions, one potential shortcoming of this approach is that the model selection procedures required to implement it (Chib, 1995; Chib and Jeliazkov, 2001) are computationally intensive and may be prohibitive when the number of geographic units is large.

Second, the assumption that the relationship '$\rho\mathbf{W}$' is homogeneous across the entire sample can be relaxed. Alternatively, one may posit a relationship that is additive and of the form '$\sum\rho_i\mathbf{W}_i$', for an exhaustive set of subunits, $i = 1, 2, \ldots, N$, across the sample. Using '$\sum\rho_i\mathbf{W}_i$' in place of '$\rho\mathbf{W}$' is appropriate when there is reasonable belief that intrinsic factors within the data-generating environment give rise to heterogeneous neighbourhood effects. Moreover, despite its complications, implementation follows easily and naturally by extending the basic Gibbs algorithm in the standard spatial regression (LeSage, 2002). Experiments (available from the authors upon request) suggest that the extended Gibbs sampling algorithm works extremely well, predicting accurately upwards of ten correlation components in a sample of only 100 observations. Nevertheless, the procedure suffers from drawbacks. The most significant drawback is that the researcher must know *a priori* the division of respective subunits across the sample.

A third modification designed to overcome the informational demands of the former procedure is a mixture-modelling approach based on Bayesian classification and discrimination. Bayesian implementation of finite mixtures (Lavine and West, 1992; Diebolt and Robert, 2004) is simple, intuitive and attractive. And when the number of components within the mixture is unknown, a modification (Richardson and Green, 1997) facilitates inference. Mixture modelling is attractive in the context of equation (1) because it allows the data itself to sample select and designate observations into the most appropriate designations corresponding to a particular form of spatial dependence. Work is currently underway to implement such a model in a sample of US congressional votes on agricultural legislation.

Finally, depicting dependence of the correlation parameter on possible sets of covariates offers potential for better understanding the relationship between spatial dependence and observable factors upon which the researcher should wish to condition inferences. To our knowledge such work has not yet been attempted. It is, however, conceivable that one could implement such a model by extension of generalised linear model methodology (Dellaportas and Smith, 1993) and that such extension offers considerable scope for improving our understanding of the nature of the forces affecting spatial dependence in bio-economic and land-use modelling. Thus scope exists for improving the robustness of inferences derived from spatial models of bio-economic and land-use change and work continues in these directions.

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Appendix I

Table A1

Literature surveyed

Source and Purpose	Context
Nelson (2002) introduces the special issue on spatial analysis for agricultural economists.	The von Thünen model of farm price land use and land rent.
Nelson and Geoghegan (2002) overview papers devoted to land use combining non-traditional data sources with novel economic and econometric models.	Net present value; discrete choice in space; multinomial logit; remotely sensed data; statistical classification and clustering; deforestation applications.
Anselin (2002) reviews classical inference for spatial correlation in linear regression focussing on pedagogic developments and spatial correlation; excludes spatial heterogeneity.	Theoretical motivations for spatial dependence; data-driven motivations; asymptotic inference; spatial lag model; spatial error model; ecological regression; ecological fallacy; spatial aggregation.
Florax *et al*. (2002) present spatial statistical techniques for capturing local differences in soil variability in precision agriculture.	Precision farming and historical yields data; spatial heterogeneity; spatial error model; spatial lag model applied to crop response in south west Niger.
Swinton (2002) captures household-level spatial influence in agricultural management and compares spatial lag and random-effects regressions.	Spatial lag, spatial error, combined lag and error model and random effects regression applied to natural-resource degradation in southern Peru.
Fleming (2004) presents techniques for estimating spatially dependent limited dependent variable models.	Classical inference; asymptotic theory; applications.
Holloway *et al*. (2002) present pedagogic development of the Bayesian spatial probit model including an empirical application to high-yielding-variety adoption decisions by Bangladeshi farmers.	Canonical normal-means model; Gibbs sampling; random-walk metropolis sampling; Bayesian spatial probit model; a sample of 406 technology adoption choices.
Mertens *et al*. (2002) analyse relationships between landscape dynamics, infrastructure, ecology, zoning policies and the evolution and organisation of livestock production, consumption and marketing in the Amazon.	One case study test site, the region of São Félix do Xingú, South of Pará; logistic regression models of land use; two periods 1986–1992 and 1992–1999; large-sample GIS datasets, $N \geq 150{,}000$; pixel units $\cong 30$ m $\times$ 30 m.
Vance and Geoghegan (2002) estimate a spatially explicit model of forest clearance in southern Mexico, and estimate the probability of deforestation.	Models of net present value of deforestation and, log-log duration; Landsat TM satellite data and household survey data; TM pixel units $\cong 0.076$ ha.

Table A1
(Continued)

Source and Purpose	Context
Müller and Zeller (2002) investigate geo-physical, agro-ecological and socio-economic determinants of land-use change in two districts of Vietnam and assess the influence of rural development policies on land-cover change.	Induced innovation; Landsat images for 1975 (multispectral scanner), 1992 (thematic mapper) and 2000 (enhanced thematic mapper); multinomial logit model; 101 villages (from a population of 191); pixel units $\cong$ 50 m $\times$ 50 m.
Munroe *et al*. (2004) analyse land-cover change in western Honduras between 1985 and 1996 and compare and contrast alternative modelling frameworks.	An area in the mountains of western Honduras; time series of remotely-sensed villages 1987–1996; Landsat images, 1987, 1991, 1996; pixel units $\cong$ 30 m $\times$ 30 m; Chomitz-Gray spatial model of land use; logit analyses of land-cover change.
Staal *et al*. (2002) assess integrated GIS and household analysis of technology adoption and land use among Kenyan smallholders.	A sample of 3330 geo-referenced farm households from surveys in western and central Kenya 1996–2000; integrated GIS-based estimation of travel times to market; logit analysis of technology choice and spatial predictions of uptake.
Bullock *et al*. (2002) demonstrate how greater use of site-specific crop response information improves variable-rate technology recommendations.	Spatial profit maximisation model; heuristic simulations of a grid of pixels; pixel units $\cong$ 41 m $\times$ 41 m = 1681 ha; comparisons of profitability with and without site-specific crop response information.
Nordblom *et al*. (2002) provide spatial predictions of impacts of releases of crown weevil to control 'Paterson's curse' and related infestations in terms of recovered pasture and stocking rates for cattle and sheep in southern Australia.	District-level analysis of geographic insect spread and attack rates; geo-referenced insect releases; non-linear concentric expansions of influence conditioned by climate zone; simulated economic benefit scenarios.
Anselin (1988) presents a comprehensive treatment of spatial econometric methods and models.	Likelihood-based inference and asymptotic theory for applied and theoretical econometric audiences.
Anselin (1999) presents treatment of spatial econometrics at an advanced level.	Likelihood-based inference and asymptotic theory for theoretical econometric audiences.
Anselin (2003) outlines a taxonomy of spatial econometric model specifications incorporating spatial externalities.	A number of diverse settings; global and local correlation; conditional and simultaneous correlations; reduced and structural forms; modelled and unmodelled effects.
LeSage (2002) describes application of Bayesian methodology to spatial econometric modelling and estimation.	Posterior probability density function analysis conditioned by the data.

Table A1
(Continued)

Source and Purpose	Context
Cliff and Ord (1975) survey the influence of spatial statistical methods in human (economic and urban) geography (with discussion).	The nature of geography; uses of classical statistical methods in geography; the spacing and size of settlements; spatial interaction and diffusion models; spatial modelling and forecasting.
Pinel-Alloul *et al.* (1988) examine the effects of body size, depth and sampling scale on spatial heterogeneity of zooplankton in Lake Cromwell, Quebec, Canada.	Four horizontally replicated samples of various taxa and sizes of zooplankton on three spatial scales at three different depths; linear regression.
Carroll and Pearson (2000) consider consequences of ignoring spatial and temporal correlation in biological conservation studies.	Sample dependence; normal linear regression bias; applications and misapplications in biological, ecological and environmental sciences.
Hertzberg *et al.* (2000) study the effects of spatial habitat on the population structure of arctic Collembola in Norway.	A field of arctic tussocks (78°55′N, 11°59′E) situated near a fresh-water lagoon with occasional sea influx; Bayesian density analyses using Poisson regression; Bayesian finite mixtures analysis of cohort structure.
Lavine and West (1992) present seminal work on Bayesian classification and discrimination using Gibbs sampling.	A four-component iterative algorithm (consisting, respectively, of Normal, inverse-Wishart, Dirichlet and multinomial distributions) for simulating draws from the posterior; application to three-component wave-form recognition.
Diebolt and Robert (1994) present seminal work on Bayesian finite mixtures using Gibbs sampling.	A four-component iterative algorithm (consisting, respectively, of Normal, inverse-Wishart, Dirichlet and multinomial distributions) for simulating draws from the posterior; application to simulated datasets.
Dennis *et al.* (2002) study spatial distribution of upland beetles in relation to landform, vegetation and grazing management in Scotland.	Principal components analysis; Getis-Ord distance statistics; analysis of within-sample clusters.
Getis and Ord (1992) produce a range of measures of statistical association.	Their potential use in descriptive statistical investigations.
Newbold and Eadie (2004) assess alternative species-habitat models to target biological and ecological conservation.	Case study of breeding mallards, Central Valley, California; models of habitat selection and prediction under alternative wetlands restoration scenarios.

Table A1
(Continued)

Source and Purpose	Context
Polasky *et al*. (2005) develop a spatially explicit model for analysing the consequences of alternative land-use patterns on the persistence of various species and on market-oriented economic returns.	Models of species persistence and the present value of commodity production; 196 pixels 400 ha^2 in Willamette Basin in Oregon; 97 terrestrial vertebrate species; conditional simulations across three classes of varied land cover.
Odoi *et al*. (2004) examine the determinants of the geographical distribution of endemic giardisis in Ontario, Canada.	Giardisis surveillance, drinking-water, socioeconomic and land-use data; southern Ontario; spatial regression models.
Rangel *et al*. (2006) present an integrated computational tool for spatial analysis in macro-ecology and biogeography.	Spatial analysis in macroecology (SAM) freeware; *Moran's I* autocorrelation coefficient; spatial lag model; spatial error model.
Shi *et al*. (2006) investigate spatial heterogeneity of multivariate relationships among white-tailed deer using geographically weighted regression.	Eight counties in Michigan, 2354 km^2; surveys of population density in 'townships' 1 square mile; Lansat TM imagery land-cover maps; landscape indices for various land-cover classes; regressions comparisons.
Claessens *et al*. (2006) study spatial distribution and ecological cycle of a canopy emergent conifer (kauri) in New Zealand.	Topographical attributes derived from a digital elevation model; intensive fieldwork geo-referencing mature kauri; 142,861 gridcells $\cong$ 30 m^2; logistic regression.
Laband and Nieswiadomy (2006) study the environmental and political factors affecting species risk of extinction in 49 US states.	The fraction of all species in a state identified by NatureServe as being 'at risk' of extinction and the fraction of species in a state listed under the US Fish and Wildlife Services Endangered Species Act; spatial lag regression model.
Newburn *et al*. (2006) incorporate spatially explicit land-use change and hedonic price models to develop targeting strategies for protecting multiple environmental benefits.	Sonoma County, California; land parcels with environmental benefits; residential and vineyards use; models of selection rules for alternative targeting strategies, environmental benefits indices, land-use change, spatial error.
McPherson and Nieswiadomy (2005) estimate an environmental Kuznets curve for threatened bird and mammalian species for 113 countries, 2000.	The notion that income and environmental degradation follow an inverse-U shape; multi-country panel data; spatial lag and spatial error models.

Table A1

(Continued)

Source and Purpose	Context
Grossman and Krueger (1995) examine the reduced form, inverted-U-shaped relationship between per capita income and environmental indicators, including air pollution, and fecal and heavy metals contamination of river basins.	Random effects, generalised least-squares estimation applied to a panel of station sites within countries across years 1977–1988.
Epperson (1990) studies spatial distributions of genetic variation under selection-mutation equilibrium within limited-dispersal populations.	Statistical analysis of genetic structure; spatial distribution of genotypes; spatial and temporal correlation; application of theoretical simulations to populations of Ipomoea purpurea ('morning glory').
Epperson (1993) examines interactions between genetic processes and spatial structure in systems of subpopulations with migration and drift by analysing correlations of gene frequencies over space and time.	Space-time autoregressive stochastic spatial time series (STAR) models; application to simulated data.
He *et al.* (2000) use spatial autocorrelation analysis to study the distribution of genotypes and gene frequencies of a tropical endangered rainforest perennial in southwest China.	The spatial distribution of genetic variation; evolutionary and ecological plant processes; spatial autocorrelation analysis of plant genotypes, family gene frequencies, and family outcrossing rates.
Bjørnstad *et al.* (1995) propose methodology for discriminating between genetic selection and genetic drift in a population.	Mantel techniques and partial autocorrelation; a sample of Poa alpina sampled along three adjacent transects of ecological gradient from snowbed to exposed ridge at an altitude of 1370–1650 in central Norway.
Köhlin and Parks (2001) assess the impacts of household fuel-wood collection on deforestation in India.	Household model with alternative fuel-wood collection strategies in a spatial range; probit analysis; 742 households; 22 randomly selected villages in Orissa; estimates of the spatial variation in fuel-wood collection.
Pattanayak and Butry (2005) consider the economic contribution of forest ecosystems services in protecting upstream watersheds that stabilise soil and hydrological flows in downstream farms.	Case study Flores Indonesia; 494 farms; spatial lag models; spatial error models; OLS.

Table A1
(Continued)

Source and Purpose	Context
Mena *et al*. (2006) quantify deforestation in the northern Ecuadorial Amazon and determine the significance and magnitude of socioeconomic factors on deforestation at both the parish and farm levels.	Deforestation rates quantified by satellite image processing and geographic information systems; farm survey data and parish census data; spatial lag analyses of deforestation rates conditioned by various covariates.
Roberts *et al*. (2000) analyse forest fragmentation using a variety of quantitative spatial statistical tools.	Conservation ecology for woodlands in the regional municipality of Peel, southern Ontario, Canada; relational database management systems; symbolic mathematics software; spatial autocorrelation structures; directional graphing.
Kerr *et al*. (2003) construct regional scale multi-usage models to assess the dynamics of human land-use systems and carbon pools contained in ecosystems and their interaction.	Integrated carbon ecology and socio-economic model applied to national-scale data for Costa Rica; expected-utility maximising agents; carbon sequestration predictions for 2000–2020.
Schnabel and Tietje (2003) explore data analysis of heavy metal contaminated soil using multidimensional spatial regression.	A set of heavy-metal measurements in topsoil at sites in the north-west of Zurich, Switzerland, 1992 and 1993; 'Mollifer' non-parametric kernel density estimation.
Kim *et al*. (2003) assesses the benefits of air-quality improvements using hedonic pricing models that explicitly account for spatial dependence.	The Seoul metropolitan housing market; unique access to 1121 (609 owner occupied and 512 renter) geo-referenced households; spatial error and spatial lag models.
Atasoy *et al*. (2006) assess the effects of urban residential development on water quality using microdata.	Wake County, North Carolina; a unique panel of individually residentially zoned land parcels relating density in residential development to three measures of water quality; combined spatial lag and spatial error models.
Assunção (2003) present three disparate and highly innovative examples in which spatial dependence is modelled by allowing regression parameters to vary as smooth functions of the area's geographical location.	Bayesian inference for generalised linear models; hierarchical normal linear modelling; spatial autocorrelation and lag models; 'smoothing'; generalisations.
Hildreth and Houck (1968) provide the seminal presentation of the random coefficients regression.	Consistent estimation; asymptotic theory; vector auto-regression.

Table A1
(Continued)

Source and Purpose	Context
Huang and Cressie (1996) model 'snow water equivalent' data using the Kalman filter.	The availability of a rich set of spatio-temporal data; application to snow water equivalent prediction in Animas River Basin, Colorado.
Vaughan (1994) surveys the geography of resource economics.	Complementary systems; practical applications; economic development; theories of resource utilisation; environmental planning and management; explorations into human behaviour.
Bateman *et al*. (2002) examine the contributions which geographic information systems may provide to analyses of environmental and resource-economic systems in the presence of spatial heterogeneity.	Selected literature in environmental and resource economics; geographical data software; geographical questions and applications to no-market valuation, hedonic pricing, recreational valuation, benefit transfer, carbon sequestration.
Nilsson *et al*. (2003) present multidisciplinary research agendas designed to improve forecasting performance of the effects of land-use change on stream ecosystems.	The literature on water quality and environmental benefit estimation; land cover descriptions; geomorphic models and measurements; ecological data and models; Bayesian inference.
Batabyal and Nijkamp (2004) survey the extensive literature on 'the environment in regional science'.	Five key issues in the literature, namely regional economic development, environmental regulation, natural resources, international affairs and geographic information systems.
Holland *et al*. (2004) introduce the special issue devoted to spatial modelling in fisheries economics.	A workshop, 'Spatial Modelling in Fisheries Econmics', sponsored by the United States National Oceanographic and Atmospheric Administration Fisheries Office (NOAA).
Wilen (2004) discusses recent advances in the understanding of the spatial distribution of resource abundance in the oceans.	An eclectic set of forces impacting the oceans; slowly changing processes operating over large spatial scales; episodic events operating over small scales; technological advances and monitoring at fine temporal and spatial scales.
Holland (2004) compares and contrasts various assignments of spatial property rights as means of internalising the externality arising from the common property nature of fisheries.	The literature on resource rent dissipation in fisheries; paucity of literature on the optimal nature of property rights for fisheries; individual transferable quotas; territorial user rights; territorial stock-use rights; marine reserves.

Table A1
(Continued)

Source and Purpose	Context
Sanchirico (2004) develops a class of spatially explicit models designed to assess the dispersal benefits of marine reserves relative to their costs.	The notion that marine reserves increase aggregate (system-wide) catch potential when the dispersal benefits of the reserve outweigh the opportunity cost of closing the area to fishing; qualitative (comparative dynamic) analysis.
Dalton and Ralston (2004) analyse the effects of spatial closures implemented in an effort to reduce by-catch of over-fished groundfish stocks.	Data on groundfish trawling at Moss Landing Harbor, Central California, 1981–2001; bioeconomic modelling of effort; dynamic linear rational expectations development of regression equations of catch based on Euler equations.
Smith and Wilen (2004) endogenise fisher home-port choice in the bioeconomic modelling of marine reserves.	The California sea urchin fishery; models of the spatial distribution of size, the economics of diver behaviour, fish mortality, catch; spatial choice in the short and long runs; north-south switching regressions of location choice.
Hicks *et al*. (2004) present spatial models to assess some of the economic welfare losses of setting aside essential fish habitat areas.	A spatial model of fishing effort incorporating congestion effects; logbook data placing vessels in a 'ten-minute square'; observations on landings per unit effort, fishing time, area-specific revenue variance and trips; logit estimation.
Curtis and McConnell (2004) examine whether alternative assumptions about spatial information acquisition and release affect spatial decision-making.	The strong assumption that operators have complete information across sites; nested logit analysis of site choice in the Hawaii longline fishery; 113 longline vessels, 11,785 fishing sets on 11,010 trips in 1998.
Strand (2004) compares and contrasts predictions obtained from spatially aggregated and spatially disaggregated models of site choice.	Atlantic and Gulf of Mexico pelagic longline fisheries, 1996; logit estimation.
Mistiaen and Strand (2000) consider location choice of commercial fishermen under heterogeneous risk preferences.	The strong assumption that risk preferences are homogeneous; a model of fisher effort; logit estimation; data on 2599 trips by 265 vessels in eight locations in the eastern Atlantic, the Gulf of Mexico and the Caribbean, 1996.
Curtis and Hicks (2000) estimate the losses associated with incidental capture of sea turtle populations.	The Hawaiian pelagic longline fishery; conceptual model of site choice; logit estimation; post-estimation welfare loss computation.

Table A1
(Continued)

Source and Purpose	Context
Smith (2000) assesses the importance of choices between structural and reduced-form models, information decay and the complexities of spatial search and information sharing in fishing effort site selection.	Structural and reduced-form analytical developments; Bayesian updating of key parameters influencing site decisions.
Fleming (2000) discusses spatial statistical and econometric modelling of fisheries.	Preceding papers devoted to the topic.
Sanchirico and Wilen (2005) investigate the optimal spatial allocation of effort in a spatially heterogeneous natural resource system.	A bioeconomic system wherein subsystems are connected by dispersal processes and are affected by the spatial distribution of harvest effort; a spatial model of a fishery.
Sanchirico (2004) investigates the bio-economic tradeoffs inherent in enacting marine reserves in a limited-entry fishery.	Bio-economic metapopulation model; biological dispersal and connectivity; marine-reserve design; numerical simulations.
Smith (2002) analyses spatial patterns of marine resource exploitation using two, alternative econometric structures.	A rich and unique dataset on location choice among divers in the California sea urchin fishery; combined count-data and SUR estimation; nested logit estimation.
Su *et al*. (2004) present Bayesian hierarchical models of stock recruitment analysis of pink salmon.	The need to better understand factors affecting spawner-to-recruit survival rates in pink salmon populations; 43 pink salmon stocks with ocean entry points in the north-western US and Canada; Bayesian hierarchical normal-linear and generalised linear models; spatially correlated priors; model comparisons.
Lindley and Smith (1972, with discussion) present seminal results for the Bayesian hierarchical normal linear model.	The joint notions that the parameters are random variables which admit probability distribution functions and that the data in the normal linear model are i.i.d. exchangeable.
Roe *et al*. (2002) posit a spatially explicit, county-level model of the hog production sector.	Agglomeration economies, environmental regulation, firm location, hog production, market access, rural–urban interface, spatial econometrics, spatial autoregressive model.

Table A1
(Continued)

Source and Purpose	Context
Isik (2004) present a model of location and production in order to examine the impacts of environmental regulations, location factors, and agglomeration economies on the spatial structure and geographical location of dairy farming.	Agglomeration economies, environmental policy, firm location, livestock sector, spatial econometrics, spatial autoregressive model.
Florkowski and Samiento (2005) propose spatial econometric techniques to model the factors that explain the price received by pecan growers.	Pecan growing, spatial autocorrelation, spatial econometrics, spatial error model.
Voortman *et al*. (2004) employ spatial econometric techniques to characterise spatial soil variability and its effect on millet yield in Niger.	Sahelian soil variability; cation ratios; aluminum saturation; surface crusting; and their implications for millet yield functions; spatial econometric techniques; spatial autoregressive model; spatial error model.
Anselin *et al*. (2004) determine the potential for using spatial econometric analysis of combined yield monitor data to estimate site-specific crop response functions.	Argentinian corn production; precision agriculture; site-specific nitrogen management and data; spatial correlation techniques; spatial econometric techniques; variable rate technology.
Lambert and Lowenberg-DeBoer (2004) compare four spatial regression methods that explicitly incorporate spatial correlation in the economic analysis of variable rate technology in Argentina.	Yield monitor data in Argentina; variable rate nitrogen application; spatial regression models; negative spatial correlations; spatial autoregressive model; spatial error model.
Dark (2004) applies GIS and spatial regression techniques to examine the biogeography of invasive alien plants in California.	Biogeography in Californian landscapes; biological invasions; GIS techniques; spatial lag and spatial error models.
Persson *et al*. (2005) evaluate the sampling density for creation of high-resolution digital elevation models for precision agriculture purposes.	Potato yields; topographical quality indices, digital elevation models of ground cover; drainage; spatial regression techniques.
Miller (2005) incorporates spatial dependence in predictive vegetation models.	Vegetative land-cover models; satellite imagery; statistical investigations of spatial dependence; kriging.
Wang *et al*. (2005) construct a net primary production regression model based on geographically weighted regression models for forest ecosystems in China.	China; forest land cover; geographically weighted regressions; spatial autocorrelation regressions; spatial lag models.

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Source and Purpose	Context
Irwin and Geoghegan (2001) review some of the advances that have been made by geographers and natural scientists in developing models of spatial land-use change.	Alternative models of land-use change; spatial economic models.
Parker *et al*. (2003) present an overview of multi-agent system models of land-use/cover change (MAS/LUCC models).	Agent-based modelling; cellular automata and complexity theory; land-use and land-cover change models; multi-agent systems.
Pelkey *et al*. (2000) examine changes in vegetative cover across Tanzania using normalised difference vegetation index imagery.	Habitat change; a normalised difference vegetation index; protected areas; Tanzania; vegetative greenness; satellite imagery.
Nelson *et al*. (2004) estimate a spatially explicit economic model of a proposed road improvement activity in Panama's Darién province and simulate-location-specific effects on land use.	Spatial analysis and spatial modelling of land use and deforestation in developing countries; road improvements; spatial econometrics techniques; remotely sensed data; geographic information systems.
Cho and Newman (2005) examine patterns of rural land development and density using spatial econometric models with the application of Geographical Information System (GIS).	Spatial evolution of rural development; cluster analysis and clasification; GIS techniques; development objectives; population density; spatial rural development.
Bockstael and Bell (1998) provide the first application to actual household-level data of a generalised method of moments (GMM) spatial estimation strategy developed by Kelejian and Prucha.	Generalised method of moments estimation techniques; spatial econometrics techniques; asymptotic theory; spatial error model, hedonic model, residential land values estimation.
Robertson *et al*. (2006) describe modifications to spatial regression-tree analysis applied to water-quality and environmental characteristics to delineate zones with similar factors affecting water quality.	Spatial regression-tree analysis; water quality and environmental benefits estimation; regional classification schemes for water quality and environmental clusters.
Müller and Zeller (2002) investigate geo-physical, agro-ecological, and socio-economic determinants of past land-use change in Vietnam and assess the influence of rural development policies on land-cover change.	Land-use change; deforestation; geographic information systems; spatial modelling; multinomial logit estimation; two data sites in the central Vietnamese highlands.
Walker and Solecki (1999) address implementation of the biosphere reserve associated with the New Jersey Pinelands Comprehensive Management Plan.	Land use; land-cover change; ecosystem management; biosphere reserve development; GIS data; spatial error model.

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Source and Purpose	Context
Crocker and D'Souza (2002) examine the spatial and socioeconomic characteristics of a sub-set of brownfields represented by sites removed from the 'Superfund inventory'.	Superfund sites and environmental public policy debates; GIS data, spatial autoregressive model.
Munroe *et al*. (2004) present an econometric analysis of land-cover change in western Honduras.	Honduran reforestation objectives; satellite image analysis; spatial econometric models; the evolution of land-use and land-cover change in Honduras, spatial autocorrelation techniques.
Polsky (2004) estimates six spatial econometric models in order to explore how human-environment relationships associated with climate sensitivities have varied over space and time in the Great Plains, 1969–1992.	Ricardian climate change impacts; species vulnerability; spatial econometrics techniques; Great Plains agriculture; spatial autoregressive model.
Liu *et al*. (2006) examine profitability and stability of site-specific nitrogen fertiliser recommendations.	Precision agriculture; controlled inputs; stable site characteristics and time-varying weather factors; OLS and spatial regression.
Verburg *et al*. (2004) review current models to identify priority issues for future land use change modelling research.	Land-use change models and methodology; integrated assessment modelling; spatial dynamics.
Griffith (1999) illustrates statistical and mathematical sources of regional science theory using map pattern analysis as an example.	Map pattern analysis; 'new economic geography'; spatial statistics, spatial modelling; explicit spatial econometric methodology.
Rey (2000) reviews integrated econometric input-output modelling for regional economies.	Regional modelling techniques; integrated, econometric, input-output modelling techniques; explicit spatial autoregressive modelling and techniques.
Plantinga *et al*. (2002) investigate the effects of potential land development on agricultural land prices.	Land-use models and land-use policy; agricultural land prices; land development; urban spatial models; spatial error model.
Huang *et al*. (2006) estimate a hedonic model of Illinois farmland values using county-level pooled cross-section time-series data.	Farmland values literature; hedonic pricing models; spatial lag models and spatial lag methodology; swine production; pooled time-series, cross-section data.

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Source and Purpose	Context
Gustafson *et al.* (2005) investigate the relationship between environmental amenities and changing human settlement patterns between 1980 and 2000 in the Midwestern USA.	Causes of change in ecological amenities, environmental perceptions, housing density, and human settlement patterns; landscape change; predictive modelling of land-use change; spatial error model; spatial lag model.
Geweke *et al.* (1994) present seminal comparisons of different computational techniques in the estimation of the multivariate probit model.	Multinomial probit; Monte Carlo study; GHK estimator; simulated maximum likelihood; Gibbs sampling; data augmentation.
Johnston *et al.* (2002) examine spatial influence in stated-preference surveying.	The need to ascertain how spatial correlation affects stated preferences and the derived welfare estimates; alternative proposals to develop rural lands for residential purposes; habitat preservation; endangered species.
Portnov (2005) examines the effect of geographic proximity on the similarity of development rates exhibited by urban localities in Israel.	Urban cluster analysis; spatial statistics; spatial econometrics; spatial autoregressive model; Israeli development rates and predictions.
Bode (2004) utilises spatial econometric techniques to investigate interregional patterns of knowledge spillovers among West German planning regions.	Knowledge spillovers; regional innovation; spatial econometrics; Germany; spatial autoregressive model; spatial error model.
Carrington (2003) investigates the role of location in regional convergence for the case of the European Union (EU).	Regional convergence; European Union; β-convergence; spatial autoregressive model; spatial error model.
Babcock *et al.* (2005) explores the existence of wage spillovers in public sector teacher contract negotiations.	Regional wage spillovers; teacher salaries; contract negotiations; social comparisons; spatial econometrics techniques; spatial error model.
Ertur *et al.* (2006) illustrate that spatial dependence and spatial heterogeneity matter in the estimation of the β-convergence process among 138 European regions between 1980 and 1995.	β-convergence; spatial econometrics; spatial dependence; spatial regimes; geographic spillovers.
Bivand and Szymanski (1997) propose a model of contracting for natural monopolies in which yardstick evaluation of performance can be optimal.	Yardstick competition; spatial econometrics; spatial autoregressive model; garbage collection.

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Source and Purpose	Context
Buzzelli *et al*. (2003) examine how spatio-temporal changes in air pollution levels rise or fall with socioeconomic status.	Air pollution; environmental justice; GIS; kriging.
Dietz (2002) critically examines the interdisciplinary research of neighbourhood effects.	Neighbourhood effects; endogenous effects in space; the reflection problem; peer effects and spatial economics; spatial autoregressive models; spatial error models.
Immergluck (1999) analyses changes in commercial building activity throughout the 1980s for 75 central-city residential neighbourhoods in Chicago in order to identify how neighbourhood change affects commercial investment.	Spatial autoregressive model; spatial error model; neighbourhood change; commercial investment; racial and ethnic change and differences.
Mobley (2003) models hospital market pricing using price response curves estimated from California data, using spatial econometrics.	Excess capacity; health market antitrust; hospital competition; spatial econometrics; strategic pricing; spatial autoregressive model; spatial error model.
Porojon (2001) investigates the gravity model using spatial econometric techniques.	Spatial econometrics; trade forecasting; gravity model; spatial autoregressive model; spatial error model.
Murdoch *et al*. (2003) assess spatial dependence in an international treaty.	Public good 'spillins' and 'spillovers'; classical spatial probit techniques applied to the Helsinki Protocol.
Pace and LeSage (2004) introduce the special issue on spatial statistics and real estate.	Outlines of the various papers that appear in the special issue of the *Journal of Real Estate Finance and Economics*, vol. 29, 2004.
Gelfand *et al*. (2004) introduce a rich class of spatio-temporal models in order to explain house prices over time.	Geostatistical model; hedonic pricing models; index construction; spatio-temporal process; spatio-temporal estimation.
Case *et al*. (2004) report results from a competition on modelling spatial and temporal components of house prices.	Kriging; out-of-sample prediction; data snooping; local polynomial regression; smoothing regression; semiparametric models; cluster analysis; nearest neighbours; hedonic models.
Militino *et al*. (2004) examine different spatial statistics techniques in order to analyse the behaviour of used dwelling market prices.	Linear mixed effects models, spatial autoregressive models; conditional autoregressive models; kriging; hedonic pricing; geostatistical analyses and data; lattice models.

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Source and Purpose	Context
Brasington (2004) presents an application of spatial regression models to hedonic pricing and the provision of local public goods.	Analysis of the structure of local governments; consolidation; spatial autoregression; capitalisation; spatial Durbin model.
LeSage and Pace (2004) implement Bayesian estimation of spatially dependent missing data models in order to account for unsold properties in a hedonic house price model.	Spatially missing data; the EM algorithm; sparse matrices; hedonic pricing; spatial autoregressive model; spatial error model; spatial Durbin model.
Páez and Scott (2004) review spatial statistical techniques for urban analysis with examples.	Geographic Information Systems; modifiable areal unit problem; spatial association and spatial heterogeneity; spatial statistics; urban analysis.
Pace *et al*. (1998) provide an overview of spatial statistical methods and point to the relevant literature and software options.	Spatial statistics; conditional autoregressive model; spatial autoregressive model; kriging.
Pace *et al*. (2000) compare and contrast alternative model specifications in forecasting urban real estate prices.	A sample of 5243 housing price observations, 1984–1992, Baton Rouge, Louisiana.
Hardie *et al*. (2001) estimate county-level farmland and residential housing values for the mid-Atlantic region.	Farm land values models; land prices; the Mid-Atlantic region; rural development; spatial error model.
Thibodeau (2003) presents the text of the 2001 Presidential Address for the American Real Estate and Urban Economics Association.	Address concerning the factors influencing house price prediction accuracy.
Van der Kruk (2001) studies economic impacts of the provision of amenities in Dutch wetlands using spatial econometric techniques.	Housing market model; wetlands amenities models; Moran's I statistic; spatial autoregressive moving average (SARMA) spatial econometric model.
Boxall *et al*. (2005) examine the impacts of oil and gas facilities on rural residential property values in Alberta, Canada.	Sour gas, hedonic prices and property value impacts; hedonic pricing method; spatial error model.
Colwell and Munneke (2003) examine urban land prices within a non-parametric framework.	Piecewise parabolic multiple regressions splines; price surfaces; application to the Chicago metropolitan area.
Ding (2001) examines land use development patterns that combine GIS and spatial regression techniques.	GIS; spatial dependence; spatial regression; spatial probit regression.
Entwistle *et al*. (2005) estimate village-level models of the effects of population variables on the area devoted to upland crop production in Nang Rong district, Thailand.	Land-use policy and land-use modelling; agricultural extensification; households level data; spatial regression; spatial error model.

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Source and Purpose	Context
Koop and Tobias (2004) use data from the National Longitudinal Survey of Youth to estimate returns to schooling.	Unobserved heterogeneity in returns to schooling and a lack of literature that assesses it.
Tsionas (2002) implements a Bayesian stochastic frontier model with random coefficients.	Develops a random coefficient stochastic frontier model to account for firm heterogeneity in efficiency measurement and applies a Bayesian Gibbs sampling algorithm to the electric utility data of Christensen and Green (1976).
Durlauf (2004) reviews the literature on 'neighbourhood effects'.	A taxonomy of models of neighbourhood formation and a taxonomy of models of empirical applications of the former.
Holloway and Lapar (2007) present Bayesian spatial probit results for market participation amongst Phillipino smallholders and estimate both the size and the magnitude of the geographic neighbourhood and the neighbourhood effect.	A vast literature on smallholder market access and neighbourhood effects; the notion that adoption decisions may be geographically correlated; the need to understand both the magnitude and geographic spread of influence; spatial probit model; Bayesian estimation and model comparison.
Chib (1995) presents and applies seminal methodology for calculating the marginal likelihood – the essential input in model comparison – using the Gibbs output.	Bayes factors; estimation of normalising constant; finite mixture models; linear regression; Markov chain Monte Carlo; Markov mixture model; multivariate density estimation; numerical standard error; probit regression; reduced conditional density estimation; stepwise algorithm.
Chib and Jeliazkov (2001) present and apply seminal methodology for calculating the marginal likelihood from the Metropolis–Hastings output.	Bayes factors; Bayesian model comparison; clustered count data; correlated binary data; local invariance; local reversibility; Metropolis–Hastings algorithm; multivariate density estimation; reduced conditional density estimation; stepwise algorithm.
Richardson and Green (1997) present seminal methodology for Bayesian analysis of mixtures when the number of mixture components is *a priori* unknown.	Birth-and-death processes within a Markov chain; classification; galaxy data; heterogeneity; lake acidity data; Markov chain Monte Carlo method; normal mixtures; predictive distribution; reversible jump algorithms; sensitivity analysis.

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Source and Purpose	Context
Dellaportas and Smith (1993) present Bayesian inference in a wide class of generalised linear and proportional hazards models.	Quadratic logistic model; Weibull proportional hazards model; log-concave density rules; adaptive sampling algorithms; automated implementation schemes.
Morenhoff (2003) studies mechanisms by which neighbourhood contexts in urban areas are related to health.	A multilevel spatial analysis of birth weight; 101,622 live births; 342 Chicago neighbourhoods.
Talen (2005) considers land-use zoning in Champaign and Urbana.	The notion that land-use zoning and measures of spatial diversity can be explicitly connected; desire for enhanced diversity; the Simpson diversity index applied to zoning block groups.
Lima and Macedo (1999) consider estimation of the spatial weights matrix in residential housing market studies.	Comparisons of Bayesian and sampling theory approaches; residential housing-market data in Belo Horizonte, Brazil.
Bin *et al.* (2006) investigate the extent to which amenities and risks in coastal housing markets are correlated.	The notion that amenities and risks are so highly correlated that conventional hedonic models cannot disentangle effects; develops improved inference for spatially correlated willingness to pay measures.
Kestens *et al.* (2006) study heterogeneity in hedonic-price housing models.	Heterogeneity of implicit prices of household type, age, educational attainment, income and the previous tenure status of buyers; expansion-term and geographically weighted regressions methodologies.
Brasington and Haurin (2006) estimate a hedonic spatial lag house price model.	A test of the value-added linkage between house prices, location and educational outcomes.
Brasington and Sarama (2007) estimate a Bayesian hedonic spatial error probit model.	Linkages between deed types, house prices and mortgage interest rates.
Cressie (1993) develops the long-considered standard text for statistics for spatial data.	Likelihood based inference.
Banerjee *et al.* (2004) present comprehensive treatments of Bayesian hierarchical modelling and analysis for spatial data and present introductions to a host of applications in the social, geo-physical and biological sciences.	The Markov chain Monte Carlo (MCMC) revolution in Bayesian inference; the lack and hitherto inaccessibility of a viable Bayesian alternative to the classic text by Cressie (1993).

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Source and Purpose	Context
Wilke *et al*. (2001) demonstrate hierarchical Bayesian modelling of spatio-temporal relationships in the geosciences.	Satellite derived wind estimates that have high spatial resolution but low global coverage and wind fields provided by the major weather centres that provide complete coverage but have low spatial resolution.
Zhu *et al*. (2003) apply hierarchical methods to the 'change of support problem' where they seek to make inferences about the values of a variable at points or in regions different from where it is observed.	The spatio-temporal setting relating ambient ozone pollution and asthma among children in Atlanta, Georgia.
Sansó and Guenni (1999) implement Bayesian truncated and multivariate normal regression models and model spatial correlation using an exponentially decreasing correlation function.	Rainfall data from 80 stations in the Venezuelan, state of Guárico consisting of accumulated monthly rainfall spanning 16 years.
Huerta, Sansó and Stroud (2004) propose a model for spatial and temporal interpolation and prediction of ozone concentrations.	Hourly reasons of ozone concentrations over Mexico city; time-varying regression of the observed readings on air temperature; combined time varying spatio-temporal models.
Agarwal *et al*. (2005) analyse deforestation rates using hierarchical spatially explicit Bayesian regression models.	The need for more detailed explanatory models predicting deforestation rates; hierarchical modelling techniques that allow the analyst to accommodate misalignment between the land-use (response) layer and the explanatory data layers; application to the eastern wet-forest zone of Madagascar, a global rain forest 'hot-spot.'
Fuentes (2001) compares maximum likelihood and Bayesian approaches in the context of developing methodology for 'high-frequency kriging' for non-stationary environmental processes.	Emissions reductions mandated by the Clean Air Act Amendments of 1990; a stationary isotropic random field within which parameters are allowed to vary spatially; a fitting algorithm using spectral methods; comparisons with Bayesian approaches.
Brown *et al*. (1994) develop Bayesian methodology for spatial interpolation of vector-valued random response fields.	Informative hierarchical prior modelling in which parameter uncertainty at the first level is completely articulated. Application to a set of monitoring stations data in southern Ontario.
Müller *et al*. (2001) model geographic patterns of child growth and assess dependence on a wide range of environmental, dietary and socio-demographic variables.	Anthropometric data from the 1982/83 Papua New Guinea National Nutrition Survey; hierarchical Bayesian spatial models.

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Source and Purpose	Context
Best *et al.* (2000) develop Bayesian spatial Poisson regression models for assessing health and exposure data measured at disparate resolutions.	Raw data for ecological regressions, including disease cases, environmental pollutant concentrations and the reference population at risk, measured at different levels of spatial aggregation; hierarchical Poisson regression; application to the effect of traffic pollution on respiratory illness in children in Huddersfield, UK.
Handcock and Wallis (1994) develop Bayesian methodology for predicting mean areal temperature across the northern and central United States.	A stationary spatio-temporal Gaussian random field model; short-memory temporal dependence; long-memory temporal dependence; calibration of changes in mean areal temperatures.
Gelfand *et al.* (2004) develop spatio-temporal models of house price moments, extending all house-price index models currently in the literature.	A rich class of models in which properties are geo-referenced and their associated selling prices are modelled by a set of temporally indexed stochastic processes.
Smith and LeSage (2004) develop individual-effects Bayesian spatial probit models.	Spatial autoregression; binary choice; Markov chain Monte Carlo; 1996 US presidential election; 3110 counties.
Kamarianakis (2006) develops hierarchical Bayesian models for spatial time series as alternatives to spatial seemingly unrelated regressions methodology.	Extends and refines the hierarchical Bayesian space time model of Wilke *et al.* (1998).
Gelfand *et al.* (2007) present further thematic development of the key idea that permitting spatial heterogeneity across regression coefficients leads to improved, robust inference.	Rich data on condominium sales in Singapore including 68,000 transactions on 1374 buildings; multilevel hierarchical spatial point processes; MCMC implementation; model selection.
Diggle and Ribeiro (2002) discuss alternative classical and Bayesian hierarchical methodologies for inference in Gaussian geostatistical modelling.	Data on May–June precipitation rates at 143 locations over 33 years in Paraná state, Brazil.