

City-wide relationships between green spaces, urban land use and topography

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Abstract The growing proportion of human populations living in urban areas, and consequent trends of increasing urban expansion and densification fuel a need to understand how urban form and land use affect environmental quality, including the availability of urban green spaces. Here we use Sheffield as a case study of city-wide relationships between urban green space extent, quality (vegetation cover and tree-cover), and gradients in urban form and topography. The total area of buildings and length of the road network are equally strong negative predictors of extent of green space, while the former predictor is a more important negative influence upon green space quality. Elevation positively influences extent of green space but negatively influences tree-cover. In contrast, slope of terrain positively influences green space quality and is the best predictor of tree-cover. Overall housing density is a more important negative predictor of extent of green space and tree-cover than the densities of individual housing types. Nevertheless, the latter are more important influences upon levels of vegetation cover. Threshold effects of densities of different housing types suggest opportunities for optimising green space quality, with implications for housing policy. Variation in ecological quality of green space may partly reflect different historical intensities of industrial activity.

Keywords Housing density · Normalised difference vegetation index · Tree-cover · Topography · Urban form

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Introduction

Urban areas presently cover about 4% of global land area (UNDP et al. 2000) with continued growth predicted to result in more than half of the world's human population living in urban areas by 2007 (United Nations 2004). This growth is primarily a consequence of a combination of human population increase, development, and social trends, with the relative importance of these factors varying between regions. For example, since the late 1940s, substantial growth in the urbanisation of the UK (ca. 7% of land area presently urbanised; Fuller et al. 2002) has accompanied an increase in population from approximately 50 to 60 million, as well as per capita increases in real GDP and average life expectancy, and (in recent decades) a marked trend towards more people living alone (Bennett and Dixon 2006). As a consequence, about 90% of the population of the UK now lives in urban areas (ODPM 2001).

Given the above trends, the quality of urban environments has increasingly been regarded as an important issue. In particular, the extent, composition and access to green spaces within urban areas have been shown to have significant impacts on the quality of life of urban populations. First, evidence is gathering in support of benefits for human physical and mental well-being (Ulrich 1998; Dunnett and Quasim 2000; Takano et al. 2002; CABE Space 2004; Galea et al. 2005). Second, benefits are evident through a diverse array of economic impacts, including those on house prices, the costs of heating and cooling buildings, and the ease of attracting businesses and employees to areas (e.g. Bolitzer and Netusil 2000; Luttik 2000; Morancho 2003; CABE Space 2004). Third, the extent and quality of urban green space has been shown to have important influences on the provision of ecosystem services (e.g. clean air and water, climate regulation), ecosystem resilience and biodiversity (e.g. Bolund and Hunhammar 1999; Pauleit and Duhme 2000; Er et al. 2005; Gaston et al. 2005a; Kühn and Klotz 2006; Colding 2007).

Such green spaces include public parks, sports fields, derelict land, edges of roads, railways and waterways, private gardens, allotments, and encapsulated remnant patches of natural vegetation as well as individual street trees that form a component of the 'urban forest' (Pauleit 2003; Colding 2007). Their coverage and composition varies in complex ways across urban areas (Duhme and Pauleit 1998; Pauleit and Duhme 2000; Pauleit et al. 2005; Gaston et al. 2005a), and is intimately associated with urban form, the patterning of the features of urban areas. To date, emphases on understanding these associations have primarily been concerned with categorising and quantifying the different forms of green space (e.g. Brande et al. 1990; Swanwick et al. 2003), comparing their characteristics and influence on environmental performance across relatively small numbers of contrasting study areas (e.g. Pauleit et al. 2005; Tratalos et al. 2007), and how temporal change in green space extent affects such performance for the same areas (Pauleit et al. 2005). Such studies have undoubtedly provided many valuable and complementary insights, but the existence and form of broad relationships remains hard to extract. Key issues concern the need to understand the continuum of variation observed across entire urban areas, particularly with respect to the shape of relationships between the extent or quality of green space and different components of the urban built environment. The latter components include key variables such as, for example, building or housing density, the density of particular kinds of buildings or housing, and the length and complexity of the road transport network. For convenience in this study, we refer to these collectively as measures of 'urban form', while acknowledging that this constitutes a considerably more restricted and simplified definition of the term than is recognised by most urban planners. A further dimension that influences

the spatial relationships between green spaces and the urban built environment is the topographic landscape, especially its components of elevation and slope of terrain.

The need for an improved understanding of the relationships between green space and urban form is particularly marked in regions which whilst already heavily urbanized are expected to become yet more so. For example, in the UK the human population, already high by European standards, is projected to grow by a further 5% on the 59.7 million of 2005 to 62.7 million in 2021 (following the “medium-fertility assumption”; United Nations 2004). Combined with social changes this means that around 3.8 million additional houses may be required before 2021 (DETR 2000). Moreover, in order to protect greenfield sites, the government target is that 60% of new houses must be built on brownfield sites or in place of existing buildings (DETR 2000), and housing planning guidelines therefore recommend an increase in the current density of new houses from 2,000–2,500 to 3,000–5,000 houses km⁻² (ODPM 2002). Evidence suggests that such densification will result in declines in availability of urban green spaces over time if more attention is not paid to understanding environmental and landscape dynamics affecting their management and preservation (Pauleit et al. 2005).

In this paper, we document city-wide patterns of variation in the extent and quality of green spaces in relation to gradients of urban form and topography. Using the city of Sheffield, UK as a case study, our primary aims were threefold. First, we sought to document the spatial variation in measures of urban green space, urban form, and topography, and the simple patterns of covariation between these variables. Second, we sought to identify the more detailed relationships between different quantitative and qualitative measures of urban green space; we predicted that these would exhibit rather different spatial patterns, reflecting variation in the different pressures and historical influences across the city. Third, we sought to determine how well, and which combinations of, urban form and topographic variables predicted variation in the quantity and quality of urban green space.

The work reported here is part of a broader project assessing the sustainability of a variety of urban forms in UK cities (<http://www.city-form.com/>), and one of a growing number of ecological studies using the city of Sheffield as a focal system (Thompson et al. 2003, 2004, 2005; Gaston et al. 2004, 2005a, b; Smith et al. 2005, 2006; Fuller et al. 2007, 2008).

Materials and methods

Study site

The city of Sheffield, South Yorkshire (53°23'N, 1°28'W) is centrally located in England. With a human population of ca. 513,000, it is the fifth largest municipality in the UK, and the ninth largest urban area. The administrative boundaries of the city extend over a region of more than 360 km². This includes substantial areas of the Peak National Park and farmland where the density of buildings is very low. For the purposes of this study, therefore, we limited considerations to the smaller predominantly urbanised area, in which nearly all of the human population live. To the east this is principally defined by the boundaries of the city of Sheffield and the neighbouring borough of Rotherham, to the south by the Derbyshire/South Yorkshire county boundary, and to the north and west by the demarcation between 1×1 km cells having more or less than 25% coverage by residential and industrial zones (as judged by eye from Ordnance Survey 1:25,000 scale maps). This area has an extent of approximately 160 km².

Environmental data

We compiled data on three complementary measures of the overall availability and quality of green space, two topographic metrics, and eight measures of urban form, using a 250- \times 250-m equal-area sampling grid overlaid across a map of Sheffield.

Ordnance Survey (2006) MasterMap data in a GIS were used to calculate the areal extent of urban green space within each grid cell. We summed the areas contributed by the gardens layer in MasterMap and that of all other polygons that were classified as non-sealed, hence ‘natural’ surfaces, to give estimates of the overall extent of green space. This estimate does not account for the fact that the gardens layer includes areas which contain sealed surfaces (patios, paths etc.), albeit at a fine scale, nor that the quality of other ‘natural’ areas layers, in terms of vegetation cover, are likely to be highly variable. We therefore used a cloud-free QuickBird satellite image of Sheffield taken in June 2005 to derive the Normalised Difference Vegetation Index (NDVI) as an estimate of overall levels of plant primary productivity. The mean NDVI per grid cell gives a measure of overall quality of green space as defined in terms of productivity, which is also influenced by areal extent of vegetation cover, hence giving an overall indication of the relative contribution to ecosystem performance. Finally, we calculated the overall area of woody vegetation (trees and shrubs) in each grid cell, hereafter referred to as tree-cover. The latter was determined using a GIS dataset in which polygon areas of contiguous woody vegetation cover were created by digitising from aerial photographs taken in the summer months (June to August) of 2002. Solitary trees and shrubs down to a crown area of 10 m² were included as separate polygons. Tree-cover data were only available for 2,344 grid cells coinciding with City of Sheffield electoral wards.

The two topographic predictor variables tested were mean elevation (meter), and slope of terrain (degree angle). These variables were computed from 10-m resolution Ordnance Survey Land-Form PROFILE Digital Terrain Mapping data (available at: <http://edina.ac.uk/digimap/index.shtml>).

Measures of urban form we use as predictor variables were total housing density (households per hectare); housing density sub-divided by housing type; total length of roads (meter); total number of road junctions (nodes); and total area of buildings (square meter). Total housing density was selected because of its more general association with urban garden areas. The densities of different housing types were selected because of their likely contrasting association with urban garden components of green space as well as public green spaces. We selected the total area of buildings since this is a more generally applicable city-wide measure of the urban buildings footprint than, for example, the area of commercial buildings. We used length of the road transport network and number of road nodes since these will tend to be associated with the degree to which green spaces are fragmented which will in turn have consequences for vegetation and tree-cover.

Housing density variables were calculated using UK 2001 Census data in combination with OS MasterMap data. Residential areas in Sheffield, as in most urban areas of the UK, comprise four principal types of dwelling: blocks of apartments (many adjoining dwellings, on more than one level), or terraced (two or more adjoining dwellings), semi-detached (one adjoining dwelling), and detached (no adjoining dwellings) housing, usually built in rows. The buildings polygon layer from MasterMap, overlaid with the UK Census output areas layer, was used to calculate the total area of all buildings with a footprint of ≤ 500 m² within each output area. This was then used as the best approximation of where three of the four housing types (detached, semi-detached, and terraced) were most likely to occur, since none of the buildings with a larger footprint will belong to any of these housing types. The proportion of all buildings (with the same ≤ 500 m² footprint) for a given output area, that fall within each grid cell, was

then used to allocate the numbers of households according to housing type (detached, semi-detached, and terraced) from each ward. A similar method was used to allocate households in blocks of flats to each grid cell, except the criterion of $\leq 500 \text{ m}^2$ was not implemented since this type of housing may occur even in very large buildings. The total numbers of houses by housing type were then summed to give total numbers of houses per grid cell. All housing density values were then converted to per hectare estimates.

Subsets of the Ordnance Survey (2006) MasterMap data that could be classified into separate buildings and roads layers were additionally used to compute the total area of buildings (hereafter also referred to as the ‘buildings footprint’), the total length of the road network, and total number of road junctions, within each grid cell.

Analyses

Before analysing the relationship between urban green space and urban form, we assessed the equivalence of our three measures of urban green space through inspection of the results of separate regressions of NDVI on overall extent of green space and on tree-cover, and of tree-cover on overall extent of green space. Overall extent of urban green space is effectively a proportional measure, and was normalised with a logit-transformation prior to analyses. NDVI required no transformation, while tree-cover was normalised using a square-root transformation. Since the residuals of OLS regressions retained significant levels of spatial autocorrelation, hence violating the assumption of independent errors and casting doubt on parameter estimates (Legendre 1993; Lennon et al. 2000), we implemented generalised least squares (GLS) modelling methods, fitting an exponential spatial covariance structure (since this was the best-fit choice among spatial covariance options) using the semi-variogram of OLS residuals to estimate the distance range (ρ) over which spatial autocorrelation is modelled. British National Grid coordinates of grid cell centroids were used as spatial variables and all models were implemented in SAS version 9.1.3. The spatial pattern of residuals of each of the regressions was explored by mapping them in a GIS.

The major gradients in environmental variation across Sheffield were explored using principal components analysis (PCA), and by calculating the correlation coefficients for all pairwise relationships among environmental variables. Tolerance levels ($1 - R^2$) were also estimated in order to assess the extent of collinearity among predictor variables (Quinn and Keough 2002) used in the modelling of availability of urban green space (see below).

We investigated the relative importance of different measures of urban form in predicting each of the three measures of green space. We used backward stepwise removal procedures to determine minimum adequate models (MAMs) for each of our three measures of urban green space. Two alternative MAMs were obtained for each measure of urban green space, one in which total housing density was included alongside other predictors prior to stepwise removal being implemented, and another in which total housing density was excluded from the outset of model-building. This enabled an assessment of whether inclusion of total housing density and/or the densities of particular housing types contributed to best-fit MAMs, as indicated by inspection of the Akaike Information Criterion (AIC) as a measure of overall model fit (Burnham and Anderson 2001). Single-predictor models were also computed for each combination of our three dependent variables and each urban form predictor variable. In each case the relative fit of first linear and then both linear and quadratic terms for each predictor was tested in order to compare the fit of linear and simple non-linear relationships. Since explained variance cannot be derived for spatial GLS models, we computed adjusted R^2 for equivalent OLS models (i.e. those including the same predictors) only as an indication.

Results

City-wide variation in measures of urban green space, topography and urban form

Total extent of green space and NDVI showed quite similar spatial distribution, with tree-cover area being somewhat distinct (Fig. 1a–c, respectively). The elevation and slope maps illustrate the predominantly y-shaped configuration of the Don and Sheaf river valleys intersecting at the city centre (Fig. 1d,e). Buildings area, total length of roads, and total number of road nodes, all showed a broadly similar pattern with highest values corresponding to the same y-shaped river valley configuration (Fig. 1f–h, respectively). Moving outwards from the city centre to the urban periphery there is a discernable overall trend (although not a universal one) for turnover in zonation of the peak densities of the four different housing types, starting with blocks of flats progressing through terraced housing to semi-detached housing and finally detached housing (Fig. 1i–l, respectively). The pattern for overall housing density showed a distinct trough along the y-shaped configuration of built-up area across the city centre, with peaks corresponding to areas of mainly terraced or semi-detached housing (Fig. 1m).

The plot of factors 1 and 2 from the PCA of these variables gives a visual summary of which gradients were strongly positively or negatively correlated and which groups of variables were orthogonal to each other (Fig. 2). The major axis of variation across the city corresponding to factor 1, is essentially an urban densification gradient representing the positively co-varying gradients of the total buildings footprint, total road length and number of nodes in an area, these being negatively associated with our three green space metrics, especially overall extent of green space. The orthogonal axis of factor 2 comprised the major east-west topographic gradients across the city, especially that of elevation but to a lesser extent also slope of terrain, as well as variation in the density of detached housing with which topographic metrics were more-or-less positively associated. The orientations of arrows indicating densities of the remaining three housing types reflect their progressively greater association with (and contribution to) the urban densification gradient of the major axis. However, the first and second major axes only account for 38 and 18%, respectively, of recorded environmental variation across the city.

The correlation coefficients for pairwise relationships among environmental predictors (Table 1) broadly confirm those indicated by factors 1 and 2 of the PCA. Tolerance levels were greater than 0.1, indicating sufficiently low levels of collinearity for all predictors except total housing density (Table 1). Since the latter showed a very high proportion of variance explained by all other predictors combined, its contribution to model-building was assessed with caution (see below).

Relationships between different measures of urban green space

The regressions for all three comparisons of our three measures of urban green space were highly significant (Table 2) and showed a variety of relationships (Fig. 3). NDVI regressed on total extent of urban green space showed better fit (lower AIC and higher OLS-derived R^2) than NDVI regressed on tree-cover (Table 2). The former relationship was accelerating-positive

Fig. 1 Environmental surfaces for Sheffield at 250- \times 250-m cell resolution: **a** extent of green space (m^2); **b** vegetation cover (NDVI); **c** tree-cover (m^2); **d** elevation (m); **e** degree angle of slope; **f** buildings area (m^2); **g** road length (m); **h** road nodes (junctions); **i** density of households in blocks of flats; **j** terraced housing density; **k** semi-detached housing density; **l** detached housing density; and **(m)** total housing density. All housing densities were measured as households per hectare

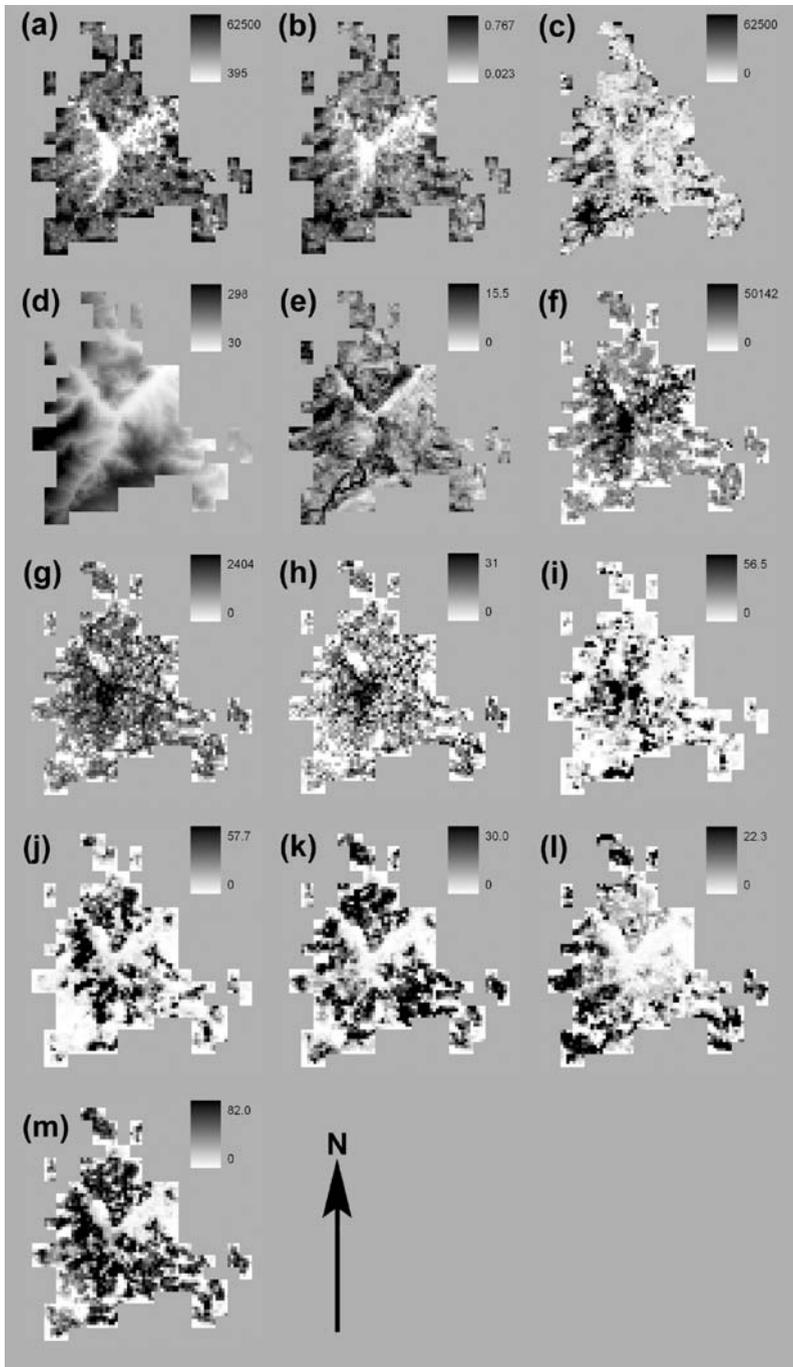
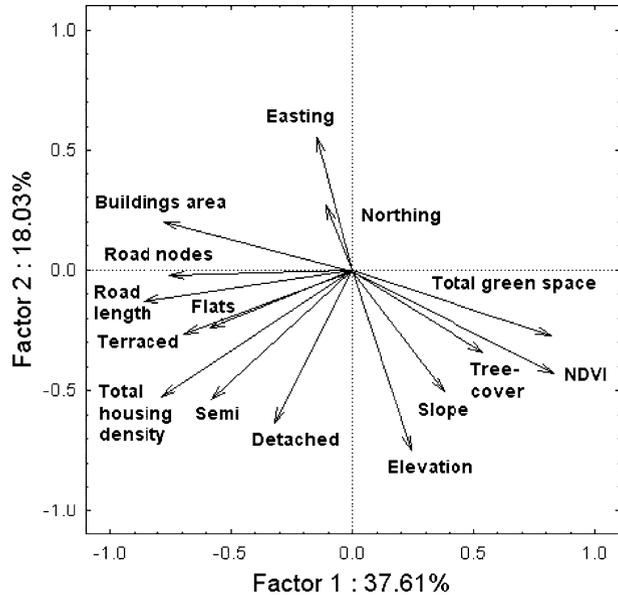


Fig. 2 PCA factors 1 and 2 loadings for measures of green space, topography, urban form, and spatial location (Easting and Northing). Percent variance explained by each axis is indicated. Abbreviations are as follows: Detached = density of households in detached housing; Flats = density of households within blocks of flats; Terraced = density of households in terraced housing; Semi = density of households in semi-detached housing; Road nodes = total number of road junctions in each grid cell; NDVI = Normalised Difference Vegetation Index



(Table 2, Fig. 3a) while the latter was decelerating-positive (Table 2), although essentially polygonal space-filling (Fig. 3b). The best-fit relationship for tree-cover regressed on total extent of green space was positive-linear (Table 2) even though the scatter-plot was again polygonal space-filling (Fig. 3c). Although the AIC of the latter model is not comparable with the former two models (having a different dependent variable), the OLS-derived R^2 indicated the lowest estimate of variation explained among the three comparisons (Table 2).

The residuals of each of these relationships show strong spatial patterning across Sheffield (Fig. 4). Extent of green space gives negative residuals (hence over-predicts NDVI) mainly in northern and eastern sectors of the city, and in built-up areas of the city centre (Fig. 4a), and positive residuals (hence under-predicts NDVI) in western and south-western areas (Fig. 4b). In contrast, tree-cover over-predicts NDVI in the most built-up areas of the city centre coinciding with the main river valleys (Fig. 4c) and under-predicts NDVI mainly at the periphery of the city (Fig. 4d). The residuals for green space as a predictor of tree-cover are rather similar to those for the latter as a predictor of NDVI (Fig. 4a and b), with over-prediction of tree-cover mainly in northern and eastern sectors (Fig. 4e), and under-prediction in western and south-western sectors (Fig. 4f). However, green space does not over-predict tree-cover in built-up areas of the city centre (Fig. 4e) to the extent that it does so for NDVI in this part of the city (Fig. 4a).

Urban form and topography as predictors of quantity and quality of urban green space

Best-fit MAMs for the overall extent of green space indicate the roughly equal and primary importance of the total area of buildings and the total length of roads as negative predictors (Table 3). Total housing density is of secondary importance, showing a decelerating negative non-linear relationship. Having accounted for the buildings footprint and total housing density in the model, the density of semi-detached housing has a predominantly positive relationship with overall green space, while density of terraced housing and especially of housing in blocks of flats show predominantly negative relationships. Model-building in which total

Table 1 Correlation coefficients for pairwise relationships among nine predictors of urban green space, and tolerance values ($1 - R^2$) for each predictor (Quinn and Keough 2002)

Predictor	Elevation (m)	Slope (degrees)	Road nodes	Road length (m)	Detached density	Semi-density	Terraced density	Flats density	Total housing density	Buildings area (m ²)
Elevation										
Slope	0.27									
Road nodes	-0.15	-0.24								
Road length	-0.08	-0.18	0.85							
Detached density	0.33	0.03	0.22	0.32						
Semi-detached density	0.18	0.01	0.34	0.54	0.54					
Terraced density	-0.05	-0.02	0.45	0.58	0.21	0.55				
Flats in blocks density	0.05	-0.02	0.42	0.49	0.15	0.29	0.50			
Total housing density	0.13	-0.02	0.51	0.69	0.59	0.85	0.76	0.61		
Buildings area	-0.24	-0.30	0.50	0.58	0.19	0.28	0.43	0.41	0.49	
Tolerance ($1 - R^2$)	0.73	0.84	0.25	0.24	0.39	0.16	0.29	0.35	0.05	0.53

Abbreviations are as follows: detached, semi-, terraced and flats density refers to densities of households for each of these respective housing types. All measures of housing density were \log_{10} -transformed. All housing densities were measured as households per hectare

Table 2 Spatial GLS models of pair-wise relationships between three measures of availability of urban green space: total extent of green space; Normalised Difference Vegetation Index (NDVI); and tree-cover area (tree-cover)

Dependent	Predictor	<i>F</i> -value	AIC	<i>R</i> ²
NDVI	Extent of green space	81.95+++	-7366.5	0.763
	Extent of green space ²	68.28+++		
NDVI	Tree-cover	750.36+++	-5960.1	0.436
	Tree-cover ²	112.79---		
Tree-cover	Extent of green space	285.82+++	22301.2	0.156

+++ and --- indicate positive and negative slopes at a significance level of $P < 0.001$. Values for Akaike's Information Criterion (AIC) indicate relative model fit. An indication of variance explained is given by the R^2 of equivalent OLS models

housing density was excluded resulted in the density of detached housing entering the MAM and showing an accelerating positive slope. Note that these results are distinct from the negative slope for the densities of all four housing types in single-predictor models in which the area of buildings is not simultaneously accounted for (Table 4). The two topographic variables are significant additional predictors of extent of urban green space in both MAMs. Inspection of the parameter estimates indicates that these show a decelerating positive relationship reaching a plateau in the case of elevation, and a predominantly positive but more hump-shaped relationship in the case of slope of terrain suggesting a negative phase towards the steeper sloping terrain.

The best-fit MAM for NDVI, reflecting the distribution of plant productivity across the city, shows some important contrasts with that for the overall extent of green space (Table 1). First, the primary importance of the total area of buildings greatly exceeds that of any other predictor, as well as exceeding the importance of this predictor in explaining extent of green space. In contrast, the total length of roads is a weaker negative predictor of NDVI than of overall extent of green space, while the number of road nodes also enters as a weak but negative predictor. Compared with the MAM for extent of green space, the positive significance of slope of terrain is substantially strengthened, making it equal in significance to the total length of roads, while the hump-shaped relationship for elevation is weakened. Further differences compared with the MAM for extent of green space are apparent for the fit of the different measures of housing density. Total housing density is a much weaker predictor of NDVI, while the non-linear fit for density of detached and semi-detached housing becomes predominantly negative, and that of flats becomes positive. Exclusion of total housing density results in a better fitting MAM and leaves the slope for semi-detached housing density negative-linear and density of housing in flats non-significant.

The MAM for tree-cover adds a further dimension to the findings from the other two measures of green space. Notably, although remaining important, the significance of buildings area as a negative predictor is enormously reduced when predicting tree-cover, while the negative role of road length is entirely replaced by road nodes (Table 3). Furthermore, in contrast to the largely positive influence of elevation upon overall extent of green space, elevation is strongly negatively associated with tree-cover. Both linear and quadratic terms for slope of terrain have positive parameter estimates, indicating an accelerating positive relationship with tree-cover. Moreover, while the relative significance indicated by *F*-values associated with terms for slope of terrain appears to be lower than those for some other predictors in the tree-cover MAMs, single-predictor models show that slope gives the best-fit single-predictor relationship with tree-cover, since it has the lowest

Fig. 3 Scatter-plots of: **a** mean Normalised Difference Vegetation Index (NDVI) ~ total extent of green space (derived from OS MasterMap data); **b** mean NDVI ~ tree-cover area; and **c** tree-cover area ~ total extent of green space. Points in the scatter-plots represent individual 250- \times 250-m grid cells

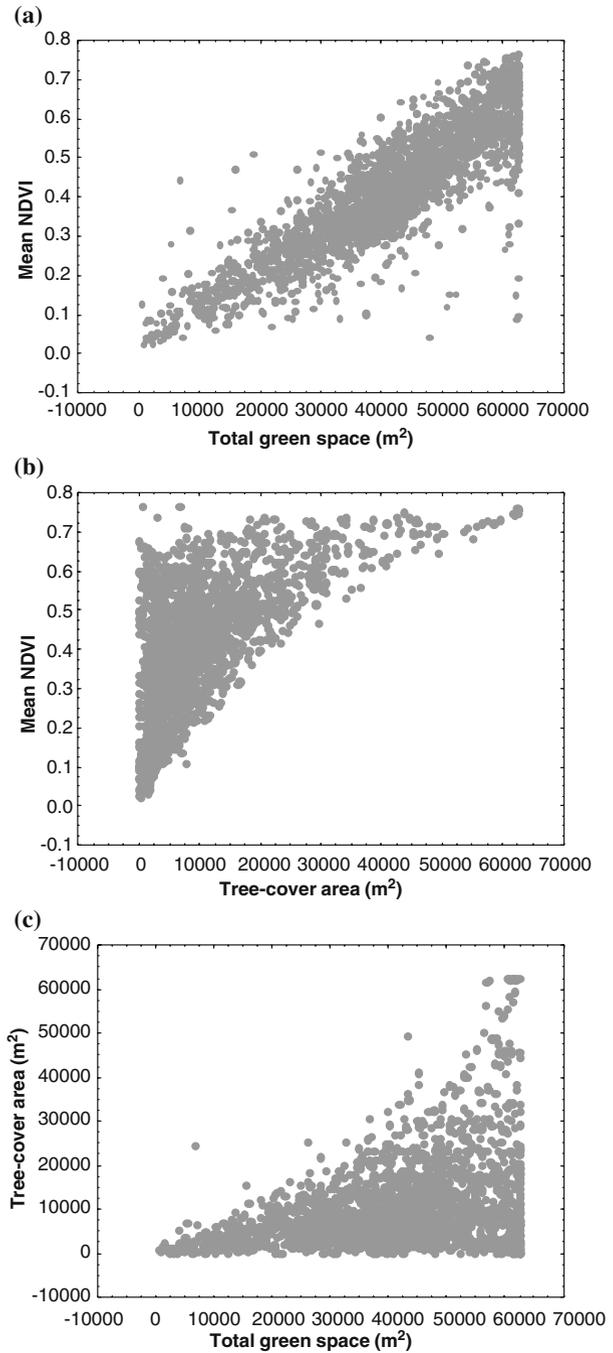


Fig. 4 Maps of the spatial distribution of residuals from regressions of: NDVI ~ total extent of green space, **a** negative, and **b** positive residuals; NDVI ~ tree-cover area, **c** negative, and **d** positive residuals; and Tree-cover area ~ total extent of green space, **e** negative, and **f** positive residuals. In each map, *areas of white* indicate where residuals of the opposite sign occur and are hence illustrated in the complementary map

AIC. Having accounted for buildings area, total housing density retains a negative overall influence on tree-cover that is more significant than the densities of particular housing types. Nevertheless, densities of detached as well as semi-detached housing showed a significant hump-shaped relationship with tree-cover. It is notable also that in the MAM in which total housing density is excluded, the density of terraced housing enters with a significant negative-linear slope, while the fit of semi-detached housing density becomes negative-linear.

Discussion

Overall, the PCA indicates that urbanisation and topography represent largely orthogonal gradients of environmental variation. However, the relatively low amount of variation explained by the first two factors of the PCA (i.e. 56%) indicates that the associations among different urbanisation and topographic factors are complex and multi-dimensional. Pair-wise correlations indicate that buildings area and slope are noticeably negatively associated, while elevation is negatively associated with detached housing density and positively associated with buildings area (Table 1). As with earlier studies, road length is positively associated with overall housing density (e.g. Hawbaker et al. 2005), but also with density of different housing types, especially that of terraced and semi-detached housing, as well as buildings area (Table 1).

Relationships between different measures of urban green space

Estimated overall extent of green space from MasterMap is clearly a useful indicator of the amount of vegetation cover estimated from satellite data, since nearly all non-sealed surface will have green vegetation of some description growing on it (Fig. 3a). However, extent of green space is a much poorer (though significantly positive) predictor of tree-cover, largely because areas of non-sealed surface vary extensively, from having no trees at all to being entirely wooded (Fig. 3c). The plant productivity estimated for an area is clearly determined foremost by the absolute levels of tree-cover present, since as tree-cover increases the lower bound to the range of possible values of NDVI increases (Fig. 3b). This demonstrates well the sensitivity of high-resolution recorded NDVI to the productive quality of actual vegetation cover on the ground (Myeong et al. 2001).

The amount of vegetation cover is to some extent either over- or under-predicted by the overall extent of green space, depending on the spatial location of a given area within the city (Fig. 4a and b, respectively). Overall extent of green space shows a similar spatial tendency in the over- and under-prediction of levels of tree-cover (Fig. 4e,f). It is highly likely that the direction of the mismatch between estimated amount of green space and these two more qualitative metrics partly represents a historical signal of the way in which different sectors of Sheffield have developed through time. Much of Sheffield's industrial base expanded from areas in close proximity to the Don and Sheaf rivers to northern and eastern sectors of the city. Hence these areas were extensively denuded of large trees and of vegetation in general (Hey 2005). Conversely, the western and south-western sectors have been, and still are, the more affluent residential areas of Sheffield where long-established

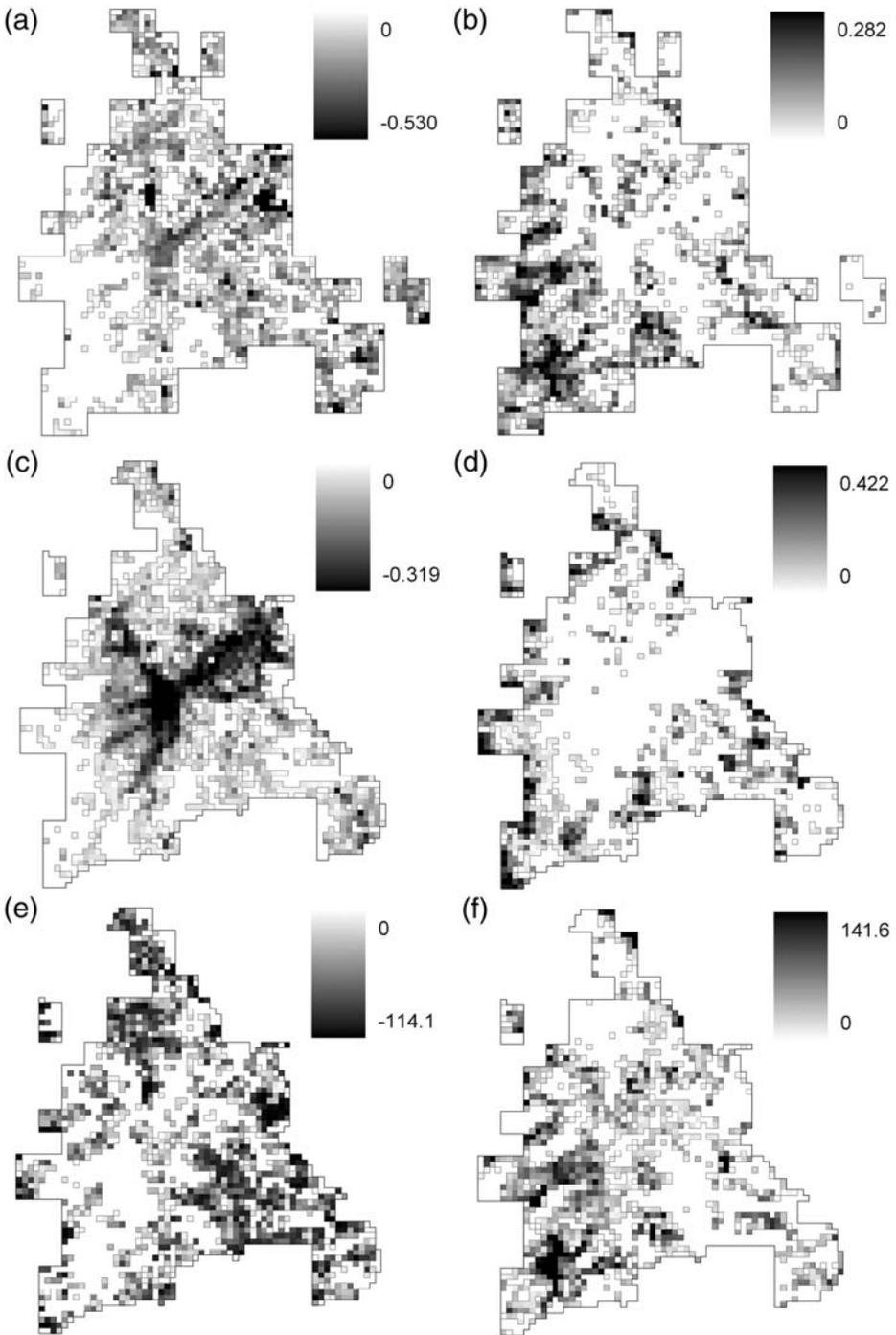


Table 3 Spatial GLS minimum adequate models (MAMs) of three measures of availability of urban green space: total extent of urban green space; Normalised Difference Vegetation Index (NDVI), and tree-cover area

Dependent	Green space		NDVI		Tree-cover	
	A	B	A	B	A	B
MAM type						
Predictor	$F_{1,2543}$	$F_{1,2545}$	$F_{1,2546}$	$F_{1,2549}$	$F_{1,2332}$	$F_{1,2334}$
Total area of buildings	438.27—	477.66—	846.92—	984.51—	69.57—	75.80—
Total area of buildings ²	57.25+++	62.88 +++	230.36+++	252.12+++		
Total length of roads	395.49—	409.93—	56.92—	67.09—		
Total length of roads ²	141.74+++	158.29+++				
Number of road nodes			7.44—	5.93-	11.18—	11.78—
Number of road nodes ²						
Elevation	20.45+++	21.93+++	7.74++	8.52++	45.73—	46.69—
Elevation ²	10.56—	11.02—	5.58-	5.95-		
Slope	31.81+++	29.03+++	196.97+++	196.13+++	12.05+++	12.75+++
Slope ²	16.28—	15.01—			7.67++	7.17++
Detached housing density		29.87—	14.19+++	12.65+++	10.85++	19.53+++
Detached housing density ²		50.63+++	16.23—	16.46—	12.87—	28.00—
Semi-detached housing density	7.98++	64.38—	11.82+++		8.61++	
Semi-detached housing density ²	5.39-	145.52+++	17.05—	15.72—	12.49—	52.09—
Terraced housing density	4.25+	11.86—				
Terraced housing density ²	9.67—	54.52+++				
Flats density	4.21+				5.59+	27.74—
Flats density ²	24.95—		7.68++			
Total housing density	246.61—		15.88—		34.33—	
Total housing density ²	169.41+++					
R^2	0.84	0.83	0.81	0.81	0.33	0.34
AIC	-509.7	-334.2	-7,728.1	-7,734.4	21,708.0	21,729.3

For each measure of green space, the relative fit of MAMs that include (A) and omit (B) total housing density prior to backward stepwise removal of terms is indicated by the AIC value (lowest is best, high-lighted in bold). + and - indicate significant positive and negative slopes, respectively, +++/---, $P < 0.001$; ++/--, $0.001 \leq P < 0.01$; +/-, $0.01 \leq P < 0.05$. The most significant F -values and slopes for each model are highlighted in bold. An indication of variance explained is given by the R^2 of equivalent OLS models that use the same combination of predictors

Table 4 Single predictor spatial GLS models of three measures of availability of urban green space: total extent of urban green space; Normalised Difference Vegetation Index (NDVI); and tree-cover area

Dependent:	Green space		NDVI		Tree-cover	
	<i>F</i>	AIC	<i>F</i>	AIC	<i>F</i>	AIC
Total area of buildings	1,194.7 —	532.5	2,340.09 —	-7285.3	237.32—	22,238.7
Total area of buildings ²	265.56 +++		605.8 +++		45.35+++	
Total length of roads	876.34—	820.7	406.97—	-5,970.6	46.82—	22,426.5
Total length of roads ²	351.96+++		83.91+++		4.72+	
Number of road nodes	506.54—	1,328.5	475.53—	-5,723.7	112.88—	22,411.5
Number of road nodes ²	235.33+++		190.59+++		44.52+++	
Elevation	16.05+++	1,879.4	11.99+++	-5173.5	35.92—	22,522.2
Elevation ²	12.45—		16.22—			
Slope	172.56+++	1,704	400.42+++	-5541.6	21.55 +++	22,134.6
Slope ²					6.48 +	
Detached housing density	328.21—	1,312.2	543.17—	-5673.3	131.38—	22,421.8
Detached housing density ²	87.14+++					
Semi-detached housing density	345.58—	1,259.4	50.85—	-5,847.4	209.46—	22,349.7
Semi-detached housing density ²	101.77+++		13.32—			
Terraced housing density	266.63—	1,455.7	557.68—	-5,684.7	4.65-	22,381.5
Terraced housing density ²	84.56+++				10.67—	
Flats density	192.59—	1,601.2	156.34—	-5414.8	24.13—	22,486.1
Flats density ²	72.96+++		51.81+++		3.93+	
Total housing density	419.97—	868	1,063.31—	-6069.0	13.78+++	22,204.7
Total housing density ²	65.89+++				108.62—	

+ and - indicate significant positive and negative slopes, respectively, +++/—, $P < 0.001$; +/—, $0.001 \leq P < 0.01$; +/-, $0.01 \leq P < 0.05$. Degrees of freedom (df) are 2,558 for linear and 2,557 for quadratic relationships in the case of green space and NDVI, and 2,342 for linear and 2,341 for quadratic relationships for tree-cover. The *F*-value(s) and AIC-values for the best-fitting model for each measure of green space are highlighted in bold

recreational parklands are located, and where steeper topography prevented more widespread industrial activity. Hence, the extent of green-space underestimates its quality in terms of vegetation, including tree-cover, in historically less industrialised, more affluent areas, and overestimates the same in areas that were previously industrial. Such differences in vegetation cover influence the quality of life of residents (McPherson et al. 1997; Pauleit 2003).

It is notable that in the built-up areas of the city centre, the extent of green space over-predicts tree-cover (Fig. 3c) to a much lesser extent than overall vegetation cover (Fig. 3a). This suggests on the one hand the greater tendency for remaining non-sealed surfaces in the city centre to be poorly vegetated, while on the other hand a greater proportion of trees in the centre are more-or-less surrounded by sealed surface. For the same reasons tree-cover appears to over-predict overall vegetation cover in the city centre while under-predicting it in areas at the periphery of the city (Fig. 3b).

Urban form and topography as predictors of quantity and quality of urban green space

The complementary nature of the three different measures of green space is again reflected in the relative importance of the measures of topography and urban form that predict them. Buildings area is a stronger predictor of the levels of plant productivity associated with green space than of the extent of green space per se and tree-cover (Tables 3 and 4). This

indicates a steeper decrease in the quality of green space, in terms of overall vegetation cover, than the accompanying decrease in extent of green space or tree-cover, with closer proximity to areas with a large buildings footprint, suggesting a marked buildings effect (Theobald et al. 1997). Conversely, the stronger negative influence of the length of the road network on the extent of green space than on levels of plant productivity and especially tree-cover (Tables 3 and 4) may reflect the tendency for at least a portion of the city's roads to be associated with vegetation cover (i.e. grass verges, shrubs and/or trees). Furthermore, in contrast to road length, the number of road nodes is a more important negative indicator of quality rather than overall extent of green space. Moreover, it is a stronger negative predictor of tree-cover indicating that the density of road junctions has a greater influence on tree-cover than simply the total length of the road network. This is likely to reflect the more active management of road junctions to maintain visibility for traffic and other factors.

The contrasting relationships between the major topographic gradients and the three measures of green space provide further revealing insight into the determinants of green space extent and quality. Largely positive relationships between the extent of green space and both elevation and slope (Table 3) reflect the rise in elevation and slope away from largely non-residential built-up areas of the city centre coinciding with the main river valleys, and a corresponding increase in gardens and non-sealed surfaces outside gardens. However, the results also indicate that overall vegetation cover (mean NDVI) and especially tree-cover is greatest on slopes rather than summits. Moreover, in the case of tree-cover, the positive association with slope and negative association with elevation may also reflect the tendency for steep river and stream banks in valley bottoms to remain wooded. This may be partly explained by the history of Sheffield, since substantial coppice woodland was managed for the steel industry within the contemporary boundaries of the city (Hey 2005). These areas were located at lower elevations than many residential areas with associated private gardens, and the impact of this on the distribution of green space is still evident today. Overall, the positive influence of slope on extent, but especially quality, of green space may be explained by the reduced incentive to build, and correspondingly greater incidence of natural areas that are of high quality in terms of overall vegetation cover and which are not associated with private gardens.

Measures of housing density are clearly important secondary predictors of green space. Total housing density is a better predictor of all three measures of green space in single-predictor models (Table 4). However, at least in the case of the prediction of levels of vegetation cover, multi-predictor models show that densities of different housing types provide a better fit (Table 3). This shows that vegetation cover varies more in relation to how density is apportioned among housing types than in relation to overall housing density. Specifically, the density of detached housing is an important positive predictor up to a threshold density, after which it becomes a negative predictor with further increase in density (Table 3). This probably reflects the varying contribution of gardens associated with detached housing as its density increases and average garden size decreases. In contrast, the negative effect of increasing density of semi-detached housing suggests no mitigating effect of this housing type in terms of the ecological quality of accompanying gardens. When total housing density is accounted for, the hump-shaped relationship for semi-detached housing density and the positive slope for blocks of flats indicates that having accounted for the negative impact of the buildings themselves, the vegetated areas accompanying them are to some extent contributing significantly to availability of plant productivity. In the case of blocks of flats, this may be due to the tendency for such developments to be surrounded by significant swathes of local authority-managed public green space.

Although best-fitting MAMs for overall extent of green space and tree-cover are those in which total housing density is included, the influence of housing type still has a significant

modifying effect (Table 3). The densities of semi-detached and terraced housing, and of housing in blocks of flats, show hump-shaped relationships with overall extent of green space. However, there is a stronger negative phase in the relationships for terraced housing and flats suggesting that the threshold density, beyond which a negative impact takes over, occurs at relatively low levels within the typical range of housing densities that these kinds of housing achieve. In the case of tree-cover, as with overall vegetation cover, the density of detached housing appears to have a positive impact up to a threshold level beyond which further increase in housing density is detrimental (Table 3). The impact of the densities of other housing types shows little if any positive phase with respect to tree-cover, and appears to be wholly negative for semi-detached and terraced housing when total housing density is not simultaneously accounted for.

Conclusions

This study shows that major gradients of urban densification and topography are important drivers of the availability and quality of urban green spaces. While both the extent of the road network and the buildings footprint in an area are roughly equal in their negative contribution to the extent of green space, the buildings footprint is the more potent negative influence on the quality of green space as measured by levels of tree-cover and especially overall vegetation cover. The greater importance of the number of road nodes as a negative indicator of tree-cover, compared with the overall length of the road network is unexpected and merits further investigation. Elevation and slope of terrain reveal a complex relationship with green space metrics, where elevation is a more positive predictor of extent rather than quality of green space, while the positive influence of slope increases between the prediction of extent and quality of green space, and is the best-fit predictor of levels of tree-cover.

Overall, the more negative effect of housing types associated with private gardens on plant productivity and tree-cover compared with actual extent of green space, may reflect several factors working in concert. First, the high housing densities associated with semi-detached and terraced housing tends to result in relatively small garden sizes. Gardens include a rather fine-scale mix of both sealed and non-sealed natural surfaces, and the proportional area that is sealed tends to increase with decrease in garden size (Smith et al. 2005). Additionally, garden size may be positively associated with the size structure of plants growing within gardens, resulting in more layered vegetation structure and larger trees growing in larger gardens (Smith et al. 2005). In conclusion, these findings suggest that housing policy should pay attention to the relative costs and benefits of different housing types and their associated densities in maintaining the extent and quality of green space in urban areas. Quality in terms of both overall levels of vegetation cover, and of tree-cover, are important indicators of the contribution of green spaces to ecosystem services (McPherson et al. 1997; Pauleit and Duhme 2000; Nowak et al. 2002; Pauleit et al. 2005).

Equally, therefore, policy should try to mitigate the effects of building at high density by, for example, retaining any pre-existing trees and large shrubs within developments, and explicitly planting new trees and shrubs on completion of developments.

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References

- Bennett J, Dixon M (2006) Single person households and social policy: looking forwards. Report of the Joseph Rowntree Foundation, York. www.jrf.org.uk/bookshop. Cited 30 May 2007
- Bolitzer B, Netusil NR (2000) The impact of open spaces on property values in Portland, Oregon. *J Environ Manag* 59:185–193
- Bolund P, Hunhammar S (1999) Ecosystem services in urban areas. *Ecol Econ* 29:293–301
- Brande A, Böcker R, Graf A (1990) Changes of flora, vegetation and urban biotopes in Berlin (West). In: Sukopp H, Hejný S, Kowarik I (eds) *Urban ecology: plants and plant communities in urban environments*. SPB Academic, The Hague, pp 155–165
- Burnham KP, Anderson DR (2001) *Model selection and multi-model inference: a practical information-theoretic approach*. Springer, New York
- CABE Space (2004) *The value of public space: how high quality parks and public spaces create economic, social and environmental value*. CABE Space, London
- Colding J (2007) Ecological land-use complementation for building resilience in urban ecosystems. *Landsc Urban Plan* 81:46–55
- DETR (2000) *Our Towns and Cities: the future—full report*. Department of Transport and the Regions, London
- Duhme F, Pauleit S (1998) Some examples of different landscape systems and their biodiversity potential. *Landsc Urban Plan* 41:249–261
- Dunnett N, Quasim M (2000) Perceived benefits to human well-being of urban gardens. *Hort Technol* 10:40–45
- Er KBH, Innes JL, Martin K, Klinkenberg B (2005) Forest loss with urbanization predicts bird extirpations in Vancouver. *Biol Conserv* 126:410–419
- Fuller RM, Smith GM, Sanderson JM, Hill RA, Thomson AG, Cox R, Brown NJ, Clarke RT, Rothery P, Gerard FF (2002) *Countryside Survey 2000 Module 7: Land Cover Map 2000. Final Report CSLCM/Final*. Centre for Ecology and Hydrology, Monks Wood
- Fuller RA, Irvine KN, Devine-Wright P, Warren PH, Gaston KJ (2007) Psychological benefits of greenspace increase with biodiversity. *Biol Lett* 3:390–394
- Fuller RA, Armsworth PR, Warren PH, Tratalos JA, Barbosa O, Gaston KJ (2008) Garden bird feeding predicts the structure of urban avian assemblages. *Div Distrib* 14:131–137
- Galea S, Ahern J, Rudenstine S, Wallace Z, Vlahov D (2005) Urban built environment and depression: a multilevel analysis. *J Epidemiol Community Health* 59:822–827
- Gaston KJ, Smith RM, Thompson K, Warren PH (2004) Gardens and wildlife—the BUGS project. *Br Wildl* 16:1–9
- Gaston KJ, Warren PH, Thompson K, Smith RM (2005a) Urban domestic gardens (IV): the extent of the resource and its associated features. *Biodiv Conserv* 14:3327–3349
- Gaston KJ, Smith RM, Thompson K, Warren PH (2005b) Urban domestic gardens (II): experimental tests of methods for increasing biodiversity. *Biodiv Conserv* 14:395–413
- Hawbaker TJ, Radeloff VC, Hammer RB, Clayton MK (2005) Road density and landscape pattern in relation to housing density, land ownership, land cover, and soils. *Landsc Ecol* 20:609–625
- Hey D (2005) *A history of Sheffield*. Carnegie Publishing, Lancaster
- Kühn I, Klotz S (2006) Urbanization and homogenization—comparing the floras of urban and rural areas in Germany. *Biol Conserv* 127:292–300
- Legendre P (1993) Spatial autocorrelation—trouble or a new paradigm. *Ecology* 74:1659–1673
- Lennon JJ, Greenwood JJD, Turner JRG (2000) Bird diversity and environmental gradients in Britain: a test of the species-energy hypothesis. *J Anim Ecol* 69:581–598
- Luttik J (2000) The value of trees, water and open space as reflected by house prices in the Netherlands. *Landsc Urban Plan* 48:161–167
- McPherson EG, Nowak D, Heisler G, Grimmond S, Souch C, Grant R, Rowntree R (1997) Quantifying urban forest structure, function, and value: the Chicago Urban Forest Climate Project. *Urban Ecosyst* 1:49–61
- Moranco AB (2003) A hedonic valuation of urban green areas. *Landsc Urban Plan* 66:35–41
- Myeong S, Nowak DJ, Hopkins PF, Brock RH (2001) Urban cover mapping using digital, high-spatial resolution aerial imagery. *Urban Ecosyst* 5:243–256
- Nowak DJ, Crane DE, Stevens JC, Ibarra M (2002) *Brooklyn's urban forest*. United States Department of Agriculture, Forest Service, North-Eastern Forest Experiment Station, General Technical Report NE-290. Radnor, Pennsylvania
- ODPM (2001) *Habitat UK National Report*. http://www.odpm.gov.uk/stellent/groups/odpm_planning/documents/page/odpm_plan_606539-02.hcsp

- ODPM (2002) Planning Policy Guidance Note 3 (PPG 3). Office of the Deputy Prime Minister. HMSO, London
- Ordnance Survey (2006) OS MasterMap User Guide. Version 6.1.1. Ordnance Survey, Southampton, UK
- Pauleit S (2003) Urban street tree plantings: identifying the key requirements. *Proc Inst Civil Eng Munic Eng* 156:43–50
- Pauleit S, Duhme F (2000) Assessing the environmental performance of landcover types for urban planning. *Landsc Urban Plan* 52:1–20
- Pauleit S, Ennos R, Golding Y (2005) Modeling the environmental impacts of urban land use and land cover change—a study in Merseyside, UK. *Landsc Urban Plan* 71:295–310
- Quinn GP, Keough MJ (2002) Experimental design and data analysis for Biologists. Cambridge University Press, Cambridge
- Smith RM, Gaston KJ, Warren PH, Thompson K (2005) Urban domestic gardens (V): relationships between landcover composition, housing and landscape. *Landsc Ecol* 20:235–253
- Smith RM, Thompson K, Hodgson JG, Warren PH, Gaston KJ (2006) Urban domestic gardens (IX): Composition and richness of the vascular plant flora, and implications for native biodiversity. *Biol Conserv* 129:312–322
- Swanwick C, Dunnett N, Woolley H (2003) Nature, role and value of green space in towns and cities: an overview. *Built Environ* 29:94–106
- Takano T, Nakamura K, Watanabe M (2002) Urban residential environments and senior citizen's longevity in megacity areas: the importance of walkable green spaces. *J Epidemiol Comm Hlth* 56:913–918
- Theobald DM, Miller JR, Hobbs NT (1997) Estimating the cumulative effect of development on wildlife habitat. *Landsc Urban Plann* 39:25–36
- Thompson K, Austin KC, Smith RH, Warren PH, Angold PG, Gaston KJ (2003) Urban domestic gardens (I): Putting small-scale plant diversity in context. *J Veg Sci* 14:71–78
- Thompson K, Hodgson JG, Smith RM, Warren PH, Gaston KJ (2004) Urban domestic gardens (III): Composition and diversity of lawn floras. *J Veg Sci* 15:371–376
- Thompson K, Colsell S, Carpenter J, Smith RM, Warren PH, Gaston KJ (2005) Urban domestic gardens (VII): a preliminary survey of soil seed banks. *Seed Sci Res* 15:133–141
- Tratalos J, Fuller RA, Warren PH, Davies RG, Gaston KJ (2007) Urban form, biodiversity potential and ecosystem services. *Landsc Urban Plann* 83:308–317
- Ulrich RS (1998) View through a window may influence recovery from surgery. *Science* 224:420–421
- UNDP (United Nations Development Programme), United Nations Environment Programme, World Bank, and World Resources Institute (2000) *World Resources 2000–2001*. Elsevier Science, Amsterdam
- United Nations (2004) *World urbanization prospects: the 2003 revision*. United Nations, New York