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Mapping an urban ecosystem service: quantifying above-ground carbon storage at a city-wide scale

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Summary

1. Despite urbanization being a major driver of land-use change globally, there have been few attempts to quantify and map ecosystem service provision at a city-wide scale. One service that is an increasingly important feature of climate change mitigation policies, and with other potential benefits, is biological carbon storage.

2. We examine the quantities and spatial patterns of above-ground carbon stored in a typical British city, Leicester, by surveying vegetation across the entire urban area. We also consider how carbon density differs in domestic gardens, indicative of bottom-up management of private green spaces by householders, and public land, representing top-down landscape policies by local authorities. Finally, we compare a national ecosystem service map with the estimated quantity and distribution of above-ground carbon within our study city.

3. An estimated 231 521 tonnes of carbon is stored within the above-ground vegetation of Leicester, equating to 3·16 kg C m^{-2} of urban area, with 97·3% of this carbon pool being associated with trees rather than herbaceous and woody vegetation.

4. Domestic gardens store just 0·76 kg C m^{-2}, which is not significantly different from herbaceous vegetation landcover (0·14 kg C m^{-2}). The greatest above-ground carbon density is 28·86 kg C m^{-2}, which is associated with areas of tree cover on publicly owned/managed sites.

5. Current national estimates of this ecosystem service undervalue Leicester's contribution by an order of magnitude.

6. *Synthesis and applications*. The UK government has recently set a target of an 80% reduction in greenhouse gas emissions, from 1990 levels, by 2050. Local authorities are central to national efforts to cut carbon emissions, although the reductions required at city-wide scales are yet to be set. This has led to a need for reliable data to help establish and underpin realistic carbon emission targets and reduction trajectories, along with acceptable and robust policies for meeting these goals. Here, we illustrate the potential benefits of accounting for, mapping and appropriately managing above-ground vegetation carbon stores, even within a typical densely urbanized European city.

Key-words: backyard, carbon pool, domestic gardens, land-use change, urban ecology, urban forestry, urban vegetation, urbanization

Introduction

During the twentieth century, the global urban human population grew tenfold and now, for the first time in recorded history, over half of the world's people live in towns or cities. This proportion is predicted to increase further, reaching 70% by 2050 (UN 2008), and urban areas continue to expand at a faster rate than any other land-use type (Antrop 2000; Hansen *et al.* 2005). Currently, approximately 4% of landcover worldwide is defined as urbanized (characterized by high human population densities or significant commercial/industrial infrastructure; UNDP, UNEP, World Bank & WRI 2000).

Increasingly, land-use policies are recognizing the need to preserve and enhance ecosystem goods and services (MEA

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2005). Yet, despite the importance of urbanization as a major driver of land-use change across the world, there have been surprisingly few attempts explicitly to quantify the provision of ecosystem services at a city-wide scale (but see Nowak & Crane 2002; Nowak, Crane & Stevens 2006; Pouyat, Yesilonis & Nowak 2006). This is likely to be a legacy of the perception that urban ecosystems have limited ecological value because they are heavily modified by humans and relatively small in size. However, with rates of urbanization set to continue, the ecology of towns and cities has become more germane to people's lives and confronting the environmental issues that they face (Gaston 2010).

One ecosystem service that is becoming a progressively more important feature of policies to mitigate climate change is carbon storage within biomass and soil (e.g. Schimel 1995; Grimm *et al.* 2008). Whilst obviously small compared with carbon emissions per unit area, the size of urban carbon reservoirs nevertheless appears to be substantial (Nowak & Crane 2002; Pataki *et al.* 2006). Indeed, the conversion of agricultural land-use to suburban cover may even result in greater carbon storage, as residential zones can exhibit higher levels of vegetation productivity than the farmed areas they replace (Zhao, Brown & Bergen 2007). However, estimates of carbon storage from urban areas in North America, where most of the research in this field has been conducted to date, cannot be simply extrapolated to Western Europe, as the patterns of urbanization are substantially different. In North America, the trend has been towards progressively more dispersed patterns of settlement referred to as 'sprawl', which are driven by the construction of large, low-density residential developments beyond the urban periphery (Hansen *et al.* 2005). In fact, across the USA, the pace at which land is transformed to urban area exceeds population growth (White, Morzillo & Aliga 2009). In contrast, within the UK and other parts of Europe, there is a tendency to densify existing urban areas (Dallimer *et al.* in press), with remaining green space being built upon, particularly domestic gardens (a phenomenon commonly referred to as 'backland development' or 'garden grabbing'; Goode 2006).

Protecting carbon storage also confers additional benefits to humans and other species residing in urban areas – a 'win-win' scenario (Rosenzweig 2003) – as maintaining and enhancing green space infrastructure within cities has significant marginal value, contributing to climate regulation (e.g. Bolund & Hunhammar 1999; Chen & Wong 2006), reducing air and water pollution (e.g. Bolund & Hunhammar 1999; Jim & Chen 2008), decreasing surface water runoff (e.g. Pauleit & Duhme 2000; Whitford, Ennos & Handley 2001), creating recreational opportunities (Miller 2006) and improving human health and well-being (e.g. Fuller *et al.* 2007; Tzoulas *et al.* 2007), as well as providing habitat for species (e.g. Fernández-Juricic & Jokimäki 2001; Gehrt & Chelsvig 2004).

Consequently, there is a need to produce estimates and detailed distribution maps of above-ground carbon stocks across cities to facilitate the development of successful resource management policies. Previously, most studies that have investigated urban vegetation cover have been restricted to inventories of trees on public lands (Zipperer, Sisinni & Pouyat 1997; Whitford, Ennos & Handley 2001). Although this approach has provided a wealth of valuable data, it does not fully account for the variation in vegetation structure, composition and management associated with the different forms of land ownership that occur within urban areas (Zipperer, Sisinni & Pouyat 1997; Whitford, Ennos & Handley 2001; Kinzig *et al.* 2005). Similarly, although national scale estimates of above-ground carbon pools, by their very nature, include urban areas (e.g. Schimel 1995; Milne & Brown 1997), they are based on low-resolution landcover classes derived from remote sensed data, which do not adequately represent the finely grained mosaic of landcovers present within cities (Gill *et al.* 2008). This paucity of information is a major hurdle to understanding, valuing and protecting ecosystem services provided by vegetation (Naidoo *et al.* 2008) at the scale and resolution most pertinent for urban landscape planning, policy making and management.

In this paper, we examine the quantities and spatial patterns of above-ground carbon stored in a typical British city, by surveying vegetation across the entire urban area (including road verges, parks, gardens, riparian zones, golf courses, industrial enclaves, schools, brownfield sites, etc.). Furthermore, we consider how above-ground carbon storage differs with land ownership, by explicitly comparing carbon densities within domestic gardens, indicative of bottom-up management of private land parcels by householders, and public land, reflecting top-down landscape policies from the local authority level (c.f. Kinzig *et al.* 2005). Finally, we assess the degree of variability between the national map for this ecosystem service and the estimated quantity and distribution of above-ground carbon within our study city.

Materials and methods

STUDY CITY

Leicester is a representative mid-sized British city, with a human population of c. 300 000 (Leicester City Council 2009) and area of approximately 73 km^2. Geographically, it is located in central England (52°38′N, 1°08′W; Fig. 1a) and experiences average annual minimum and maximum temperatures of 5·8 and 13·5 °C, respectively, 1388 h of sunshine and 606 mm of rain each year (Met Office 2009).

VEGETATION SURVEY

The landcover characteristics of the study area (see Fig. S1a Supporting Information) were determined using a GIS, comprised of polygons classified by Infoterra in their Landbase digital cartographic data set (http://www.infoterra.co.uk/landbase). In this product, each above-ground vegetation polygon (accurate to 0·25 m^2) is assigned to one of four categories effectively stratified by maximum vegetation height (classified using high resolution, 4–8 points per metre, LiDar data): *Herbaceous Vegetation* (grasses and non-woody plants), *Shrub* (woody bushes and trees with a mean height typically < 2 m), *Tall Shrub* (woody bushes and trees with a mean height generally 2–5 m) and *Tree* (trees > 5 m tall). This system of categorization was chosen as vegetation height is indicative of biomass, especially when refined using measurements of tree density (Mette, Hajnsek & Papathanassiou 2003). In

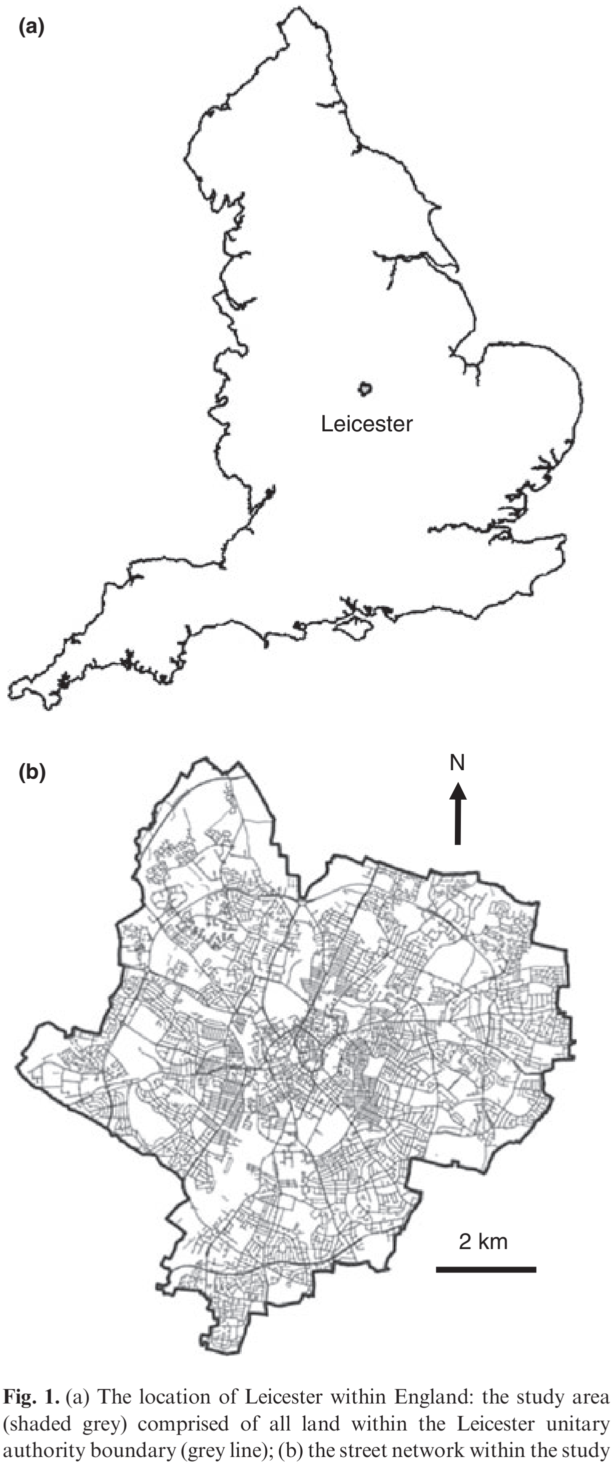

Fig. 1. (a) The location of Leicester within England: the study area (shaded grey) comprised of all land within the Leicester unitary authority boundary (grey line); (b) the street network within the study area.

addition, it broadly accounts for heterogeneity in vegetation structure across an urban area without creating too many different classes, thereby making it easier to apply the same methodological approach in other cities.

Land ownership was determined using vector data provided by Leicester City Council, which delimited publicly owned/managed land (hereafter referred to as *Public*; e.g. roadside verges, parks, recreation grounds), and Ordnance Survey MasterMap (http://www.ordnancesurveymastermap.com/) to ascertain the boundaries of private domestic gardens throughout Leicester (*Domestic Gardens*). Any remaining vegetation falling outside of these areas was considered to be of mixed ownership (*Mixed*; e.g. belonging to corporations, private individuals, abandoned industrial sites). Over 400 polygons from within these landcover–land ownership categories were subsequently ground-truthed and found to be accurately classified.

Five hundred and twenty points were randomly generated in the GIS prior to starting the vegetation survey; 130 for each of the four landcover categories (points were precluded from falling within *Domestic Gardens*; see below). The number of points created was based on previous experience of sampling in urban areas where, on average, for every site successfully visited, access to a further 1·5 would not be possible. One hundred and thirty points would therefore ensure that at least 50 sites would be surveyed in each landcover class, irrespective of land ownership (which was determined after sites were accessed but prior to analysis). During the survey, all 520 points were visited, and data were recorded from 375 sites, exceeding the desired 50 per landcover category (Table 1).

At each survey site within a landcover class, a 5×5 m quadrat was centred on the GPS coordinates of the sample point. The area of individual *Shrub*, *Tall Shrub* and *Tree* patches is highly skewed across the city, with the majority being small in size (median = 66·25 m^2; mean = 211·30 m^2). A quadrat of 5×5 m provides sufficient area for a representative sample of vegetation in larger patches, but not so large as to excessively cover smaller patches (18·2% of patches across the city are < 25 m^2, but, combined, they account for just 1·4% of the total areal extent of these three landcover categories). Within each quadrat, the proportion of ground covered by herbaceous vegetation, cultivated/bare soil (e.g. flowerbeds), trees (with a DBH > 1 cm at 1·30 m above-ground level; Condit 1998), woody vegetation (e.g. bushes, small tree saplings with a DBH ≤ 1 cm), water, litter, hard surface (e.g. tarmac) and buildings was estimated, along with canopy cover. In addition, trees present within the quadrat were identified to species or genus, and the DBH and crown height were measured (using a clinometer).

Where quadrats fell across two landcover categories, or in small vegetation patches that did not cover the entire 5×5 m area, they were always classified according to the central GPS point. During the survey, this only occurred between *Shrub/Tall Shrub/Tree* patches and *Herbaceous Vegetation*/hard surface/buildings (e.g. single trees in a residential street, surrounded by hard surface). In such instances, carbon storage was only estimated for the areal extent of the defining landcover class (e.g. if a *Herbaceous Vegetation* quadrat was partially covered by tree canopy, only the carbon density of the quadrat outside the canopy area would be calculated to prevent overestimation when scaling up, using the GIS landcover categories, to generate city-wide estimates).

In October 2009, at the end of the growing season, above-ground herbaceous vegetation was harvested from within 25×25 cm quadrats at 56 sites across the city. The quadrat locations were randomly generated in the GIS from within the *Herbaceous Vegetation* landcover category. All standing crop was removed at ground level using a cut-throat razor, bagged and removed for carbon analysis.

To survey *Domestic Gardens*, a street layer was created in the GIS (Fig. 1b), and 50 roads were selected at random. Each of these streets was visited and, if there were residential properties present and permission from a householder was granted, one garden was surveyed; in total, data were collected from 35 gardens (Table 1). The same variables were measured as above but for the entire garden, rather than a 5×5 m quadrat, the area of which was later determined from the GIS. This pragmatic approach was adopted because of difficulties in gaining entry to neighbouring gardens where the quadrat area spanned the boundary between properties, the substantial heteroge-

Table 1. The estimated number of trees and above-ground carbon stored in vegetation across the city of Leicester within the different landcover–land ownership categories. Standard errors for estimates, where they could be calculated, are given in parentheses

Landcover	Land ownership	Area (m^2)	No. Sites surveyed	Mean tree density (trees m^{-2})	Number of trees	Carbon stored in trees (kg)	Carbon stored in herbaceous vegetation (kg)	Carbon stored in woody vegetation (kg)	Total carbon stored (kg)	Total carbon density (kg m^{-2})
Herbaceous Vegetation	*Mixed*	12 419 010	30	0·00	0	0	1 775 498 (179 246)	0	1 775 498 (179 246)	0·14 (0·01)
Herbaceous Vegetation	*Public*	6 651 211	47	0·00	0	0	970 693 (92 014)	0	970 693 (92 014)	0·15 (0·01)
Shrub	*Mixed*	1 626 414	33	0·09 (0·02)	137 999 (39 410)	21 840 529 (5 292 650)	101 890 (18 045)	492 360	22 434 779 (5 292 681)	13·79 (3·25)
Shrub	*Public*	759 358	24	0·13 (0.03)	99 982 (23 872)	4 859 314 (1 293 337)	62 043 (12 006)	134 976	5 056 333 (1 293 393)	6·66 (1·70)
Tall Shrub	*Mixed*	458 261	33	0·15 (0·02)	67 767 (10 137)	5 546 458 (1 548 136)	14 804 (4095)	98 734	5 659 997 (1 548 142)	12·35 (3·38)
Tall Shrub	*Public*	124 582	17	0·18 (0·04)	22 864 (5321)	1 971 754 (392 691)	7021 (1934)	17 808	1 996 583 (392 696)	16·03 (3·15)
Tree	*Mixed*	4 399 389	72	0·15 (0·01)	667 241 (49 585)	123 200 527 (14 491 774)	103 319 (25 028)	129 782	123 433 628 (14 491 796)	28·06 (3·29)
Tree	*Public*	1 921 572	56	0·14 (0·02)	267 647 (37 471)	55 299 599 (8 372 643)	98 732 (18 697)	58 677	55 457 007 (8 372 664)	28·86 (4·36)
Domestic Gardens	*Private*	18 557 510	35	0·01 (0·003)	225 743 (58 333)	12 498 659 (4 198 163)	1 427 436 (204 572)	811 228	14 737 323 (4 203 145)	0·79 (0·23)
Total		46 917 306	347		1 489 244 (97 568)	225 216 840 (18 165 160)	4 561 436 (458 814)	1 743 565	231 521 841 (18 167 470)	4·93 (0·39)

neity often observed within individual gardens (e.g. distinct areas of lawn, flowerbed, vegetable patch, etc.) and variability in garden sizes.

BIOMASS AND CARBON STORAGE IN TREES

Above-ground dry-weight biomass was calculated for each surveyed tree using allometric equations obtained from the literature, which are primarily derived from forested areas in Europe and North America (Table S1 Supporting Information); currently, few such biomass predictors exist explicitly for urban trees. Where multiple equations were available for a species, they were combined (up to a maximum of six, using those with the most appropriate DBH or height range) to produce a generalized result (Pastor, Aber & Melillo 1984; McHale *et al.* 2009). If no species-specific allometric equation could be found, the genus or family average was substituted or, as a last resort, an equation derived from all broadleaf/coniferous trees in our sample was used (Table S1). For standing dead trees, leaf biomass was removed from the total above-ground biomass by reducing the estimate by 2·5% or 3·7% for broadleaf and coniferous species, respectively (Nowak 1993). Finally, total above-ground tree biomass was transformed to a carbon storage figure using conversion factors of 0·48 for broadleaf and 0·42 for coniferous trees (Milne & Brown 1997).

For each quadrat, tree density was calculated, adjusting for less than 100% canopy cover where applicable (e.g. in circumstances where a *Tree* vegetation patch was smaller than the area of the quadrat, such as in the case of individual street trees). In contrast, the tree density for each garden was calculated as the number of trees divided by the area of the whole land parcel. A mean tree density was then estimated for each of the nine landcover–land ownership categories (Table 1). For all the individual categories in turn, the respective mean tree density and areal extent across Leicester were multiplied together, to calculate the total number of trees occurring at a city-wide scale. On a species-by-species basis, the mean carbon stock per tree (based on the allometric estimates) was multiplied by the proportional contribution of the species to the total number of trees; this approach thus effectively accounts for both the community composition and the size distribution of trees within each specific landcover–land ownership category. The species-level results were then combined to give an estimate of the above-ground carbon store associated with trees in each of the nine categories and, subsequently, for the city as a whole.

BIOMASS AND CARBON STORAGE IN HERBACEOUS VEGETATION

The dry-weight of the above-ground herbaceous vegetation biomass samples was established after oven drying at 105 °C for 24 h. Each sample was coarsely homogenized, before five subsamples were removed. These were milled to a fine powder, re-combined, re-dried at 105 °C, and the carbon in five replicates was determined using a C:N analyser (vario EL cube, Elementar, Hanau); the percentage carbon recorded for each of the replicates was consistent for all samples (C.V. $< 1·5\%$). The carbon stock per 25×25 cm quadrat was then calculated by multiplying the percentage carbon with the dry-weight of the sample.

The mean coverage of herbaceous vegetation occurring beneath *Shrub/Tall Shrub/Tree* canopies, for each of the landcover–land ownership categories, was estimated using the data collected in the 5×5 m quadrats/gardens; although the GIS polygons accurately delineate the areas of different categories, the extent of herbaceous vegetation would be underestimated if purely derived from the digital data sets. Thus, the proportion of ground cover in each landcover–land ownership category area comprising herbaceous vegetation could be multiplied by the areal extent of each category across Leicester, to generate a corrected estimate of herbaceous cover at a city-wide scale. This was then multiplied by the average carbon stock per m^2 associated with herbaceous vegetation, as established from the laboratory analysis, to calculate the carbon store for the entire study area.

BIOMASS AND CARBON STORAGE IN WOODY VEGETATION

The average proportion of woody vegetation (please see the 'Vegetation Survey' section above for a definition) ground cover recorded in the 5×5 m quadrats/gardens was estimated for the nine landcover–land ownership categories. This was then scaled up to provide a city-wide estimate, using the respective coverage of each category across Leicester. Difficulties in gaining permission from landowners to harvest bushes because of its inherently destructive nature, and the high species diversity recorded (particularly in *Domestic Gardens*), prevented species-specific allometric equations being derived empirically. The carbon stored within woody vegetation was therefore estimated using a conversion factor of 18 t C ha^{-1}, taken from a study by Patenaude *et al*. (2003).

ABOVE-GROUND CARBON STORAGE ANALYSES

All analyses were conducted using ArcGIS (version 9.3, ESRI) and *R* (version 2.8.1, R Development Core Team 2008). Differences in carbon storage between landcover and land ownership categories were assessed using *z*-tests. Due to violation of parametric test assumptions, nonparametric Spearman's rank correlations were employed to evaluate how well the national above-ground carbon storage map (please refer to Milne & Brown 1997 for methodological details) represents the actual distribution of this ecosystem service across Leicester, as derived from this study, at a 1-km^2 resolution (that of the national map).

Results

Across Leicester, 64% of the city is covered by one of the nine landcover–land ownership categories (Table 1). Forty per cent of this area comprises *Domestic Gardens*, with a further 20% publicly owned/managed by Leicester City Council (*Public*). Outside of *Domestic Gardens*, *Herbaceous Vegetation*, *Shrub*, *Tall Shrub* and *Tree* patches accounted for 41%, 5%, 1% and 13% of the landcover, respectively.

An estimated 231 521 tonnes (95% CI = 195 914–267 130) of carbon is stored within the above-ground vegetation across the city (Table 1; Fig. 2), equating to a mean figure of 3·16 kg C m^{-2} of urban area (95% CI = 2·65–3·62). Of this total, 97·3% (225 217 tonnes; 95% CI = 189 613–260 821) consists of carbon stored in trees. A further 1744 tonnes (0·7%) is contained within woody vegetation, with the remaining 2% (4561 tonnes; 95% CI = 3706–5417) attributed to herbaceous vegetation. The mean percentage carbon content of herbaceous vegetation was 42·02% (95% CI = 41·34–42·69), corresponding

Fig. 2. The distribution of above-ground vegetation carbon across Leicester, according to the landcover–land ownership category of individual vegetation patches (Table 1): graduated shading from 0·00 kg C m^{-2} (white) to 28·86 kg C m^{-2} (dark grey).

to 0·14 kg C m^{-2} of herbaceous cover (95% CI = 0·11–0·17) or 0·06 kg C m^{-2} city-wide (95% CI = 0·05–0·07).

The only significant difference in carbon density apparent within a landcover class, between *Public* and *Mixed* land ownership, was for *Shrub* (z = 2·44, P < 0·05; Table S2 Supporting Information). Across the landcover categories, differences in carbon densities were not evident between *Domestic Gardens* and *Herbaceous Vegetation*, or *Shrub* and *Tall Shrub* (z = 1·26, P > 0·05 and z = 1·69, P > 0·05, respectively, Table S3 Supporting Information).

In total, 919 trees were surveyed and 61 species identified, 24 of which occurred as a single individual within the sample (Table S1). Eighteen trees (2%) were dead. The four most common species were all native and, when combined, accounted for approximately 40% of all trees: *Crataegus monogyna* Jacq. (14%), *Fraxinus excelsior* L. (12%), *Acer campestre* L. (7%) and *Prunus avium* L. (7%). Seven species (*Acer pseudoplatanus* L., *Betula pendula* Roth., *Crataegus monogyna*, *Fagus sylvatica* L., *Fraxinus excelsior*, *Prunus avium* and *Sorbus aucuparia* L.) were ubiquitous across all landcover–land ownership categories where trees were present, with *Acer pseudoplatanus* being the only introduced species (Table S4 Supporting Information). Tree heights, where they could be measured, ranged from 0·9 m to 34·4 m (Fig. S2a Supporting Information; median = 6·4 m, mean = 7·6 m). Within our sample, there were twenty trees over 20 m tall, and they constituted more biomass (72 790 kg; Fig. S2b Supporting Information) than the 635 trees with heights less than 10 m (56 964 kg).

When our survey-derived distribution of the carbon pool of Leicester was compared to the national estimate for above-ground vegetation carbon (Fig. 3), there was no association between equivalent 1 km^2 grid squares (Spearman's Rank Correlation: r_s = 0·015, n = 228, P = 0·409). Indeed, the national estimate predicted that the total amount of stored carbon across our study area is to be 25 299 tonnes, an underestimate of an order of magnitude in the light of our findings.

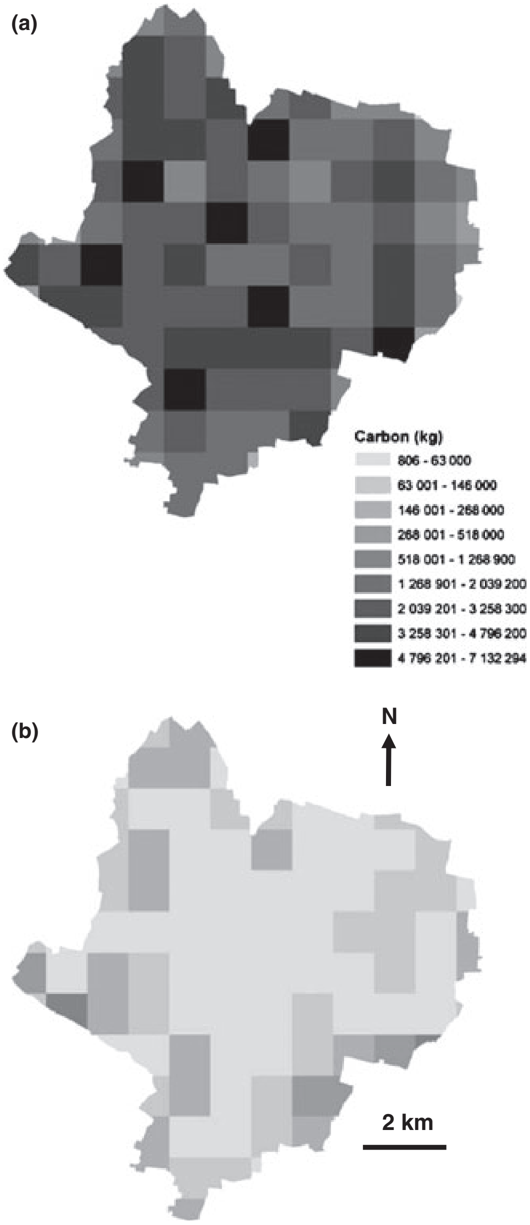

Fig. 3. The distribution of above-ground carbon stored across Leicester in 1 × 1 km grid squares: (a) derived from our sample and analysis; (b) obtained from national estimates.

Discussion

To fulfil international obligations to produce national inventories of greenhouse gas emissions by sources and removal by sinks, as well as meeting reporting requirements under the Kyoto Protocol, biological carbon emissions and sequestration arising from different land uses, land-use change and forestry must be accounted for (Dyson, Mobbs & Milne 2009). This includes recording carbon loss and capture because of the conversion of land through the process of urbanization. However, in the UK, once land is considered to be urban, biological carbon density is assumed to be zero (Dyson, Mobbs & Milne 2009).

In this study, we have demonstrated that current national estimates of above-ground carbon storage for Britain (Milne & Brown 1997) do not adequately account for the provision of this ecosystem service within urban areas, undervaluing the contribution of cities by an order of magnitude in the case of Leicester (Fig. 3). This is because the national scale map averages carbon stocks across a 1-km grid, based on a limited number of field samples and zero values for intensely built up areas. Indeed, across Leicester, there is a substantial 231 521 tonnes of carbon stored within above-ground vegetation, the equivalent to 3·16 kg C m^{-2} of urban area. The vast majority (97·3%) of this figure is attributable to the carbon pool associated with trees, rather than herbaceous and woody vegetation. To put this figure into a national context, the vegetation carbon stock for Britain is estimated to be 113·8 Tg (Milne, Tomlinson & Gauld 2001), meaning that Leicester accounts for 0·2% of the country's above-ground carbon store, yet represents only 0·03% of its area (Britain covers 228 919 km^2). Cities are, therefore, by no means depauperate in terms of carbon storage.

When compared to figures for the USA, the 3·16 kg C m^{-2} stored in Leicester exceeds the average of 2·14 kg C m^{-2} for 10 cities distributed across the country (range: 0·50–4·69; Nowak & Crane 2002). Although similar estimates have been generated for other cities around the world, the manner in which the above-ground carbon pool is determined and/or documented is not always commensurate between studies and therefore does not allow comparisons to be made (e.g. Jo (2002) reports the amount of carbon stored per unit area for 'urban' vs. 'rural' sites within three Korean cities). For *Herbaceous Vegetation* landcover, our result of 0·14–0·15 kg C m^{-2} corresponds to that reported for Chicago and Colorado, USA (0·07–0·18 kg C m^{-2}; Jo & McPherson 1995; Golubiewski 2006).

In Leicester, the majority of trees are small at, on average, 6·4 m in height, a right-skewed frequency distribution (Fig. S2). Indeed, the 20 largest trees within our sample disproportionately contribute to the above-ground vegetation biomass, providing 72 690 kg in comparison to the 56 964 kg supported by the 635 trees less than 10 m tall. This reflects the trend that has been observed in other urban areas (Nowak 1993, 1994; Britt & Johnson 2008). However, in contrast to cities in the USA, Leicester has fewer particularly large trees (defined as having a DBH $> 76{\cdot}2$ cm), but the tree density is much greater (Nowak & Crane 2002; Fig. S1b).

The errors reported here for the tree carbon estimates (Table 1) are attributed to sampling error and do not include estimation error related to the use of biomass equations. The nature of any potential bias that may be integrated into such carbon accounting is hard to predict; Jo & McPherson (2001) and McHale *et al.* (2009) have shown that, for certain species, allometric equations determined from trees grown in woodland stands underestimate biomass for individuals in an urban setting, whereas for others they overestimate. This is due to the variable patterns in tree growth, allocation, management, densities and phenology that occur in urban versus forested areas. However, where possible, we have minimized the likelihood of incorporating any systematic bias in biomass estimates for each species by using generalized results from a group of equations derived from different studies (Pastor, Aber & Melillo 1984; McHale *et al.* 2009).

Although the quantities of carbon stored within the above-ground vegetation of Leicester are not trivial, it is not a permanent sink. The carbon captured as a plant grows will ultimately be released back into the environment when it dies or is destroyed, and replacement is therefore necessary to counterbalance the carbon emitted from removed vegetation (Jo 2002; Nowak *et al.* 2002). In some instances, trees lost in urban areas will be replaced through natural regeneration, but the majority are likely to require replanting to maintain current carbon reservoirs (Rowntree & Nowak 1991). This is of particular importance on publicly owned/managed land, where trees are frequently removed or subject to surgery in response to subsidence or human safety concerns (LAEC 2007; Britt & Johnson 2008). If the number of trees is to be increased within urban areas in order partially to mitigate rising atmospheric carbon concentrations, they must be chosen and located with care to ensure a long, productive life span (Nowak *et al.* 2002). Moreover, to maximize carbon sequestration services provided by above-ground vegetation, fossil fuel consumption related to management activities (e.g. through the use of lawn mowers, chainsaws, vehicles, chipping machines) must be minimized, decomposition of waste material should be limited via long-term carbon storage solutions (e.g. land fill, making wood products), and the biomass used where possible as an alternative renewable fuel source (Nowak *et al.* 2002; MacFarlane 2009).

Another factor to be considered when deciding which tree species should be planted in an urban location is the projected future climate (Roloff, Korn & Gillner 2009). Many urban trees already suffer stress and reduced growth rates because of rising levels of atmospheric pollutants, increasing temperatures as a consequence of heat island effects, restricted rooting space and lack of water availability because of soil compaction and impervious surfaces (Freedman 1995; Gregg, Jones & Dawson 2003; Mansell 2003; Quigley 2004; Watson & Kelsey 2006; Wilby & Perry 2006). This situation is likely to be further exacerbated in the coming years as, for example, UK climate change scenarios broadly predict hotter, drier summers with more extreme weather events (Hulme *et al.* 2002). The impact on the composition of urban tree assemblages, which are frequently dominated by just a few species (e.g. four species make up 49% of the tree population of Oakland, USA – Nowak 1993; five species compose greater than half of the tree population in Athens, Greece – Profous, Rowntree & Loeb 1998), and abundance of particular species may therefore be significant. Across Leicester, four native broadleaved species were particularly common, comprising 40% of all trees recorded. Fortunately, these species are all considered drought tolerant and hardy enough to be resilient to the climate conditions forecast for the coming decades (Roloff, Korn & Gillner 2009).

Carbon density within the same landcover categories did not differ with land ownership, with the exception of *Shrub*. The *Shrub* carbon density on publicly owned/managed land was significantly lower than for mixed ownership patches, because the trees in the latter were larger in size (mean tree biomass in the *Public Shrub* category was 102 kg, compared with 330 kg for *Mixed Shrub*). In general, therefore, top-down management does not result in systematic increases or decreases in above-ground carbon densities within patches of the same landcover type.

Over 66% of the publicly owned/managed land across the city consists of *Herbaceous Vegetation*. The potential for substantially increasing the urban carbon reservoir can be illustrated by a simple back-of-the-envelope calculation, using the carbon densities for the different landcover–land ownership categories in Table 1. If 10% of the present council grassland (equating to 1 005 744 m^2) was planted and maintained with trees, an extra 28 402 tonnes of carbon could be added to the current pool (a net figure accounting for the loss of herbaceous cover and gain of tree cover). This corresponds to a 12% increase in the existing vegetation carbon stock for the city. If such a tree planting strategy was implemented by Leicester City Council, the long-term net carbon storage benefit would need to be ensured, and any potentially negative social impacts minimized (e.g. traffic safety where trees may obscure line of vision, the loss of grassland recreational space).

Within *Domestic Gardens*, carbon densities were so low that they were not significantly different from the *Herbaceous Vegetation* landcover–land ownership categories. This is due to a number of factors. First, 23·5% of garden area in Leicester comprises artificial surface. Indeed, this phenomenon of converting a garden to some form of hard standing (e.g. concreted, paved, decked) is increasing across the UK (Goode 2006). For example, a recent report has suggested that nearly half of all households in northeast England have paved over the majority of their front gardens to create off-road parking (RHS 2007). Secondly, fewer particularly large trees occur within gardens (e.g. the mean biomass of a garden tree was 120 kg, and maximum tree height recorded within a garden was 16·7 m, but the tallest tree in our sample was 34·4 m). If community initiatives were put in place by policy makers to encourage tree planting, resulting in 10% of the existing 159 789 urban gardens containing one more tree, there would be 927 tonnes more carbon (assuming they grew to an average size for a garden tree) stored in above-ground vegetation across the city. However, achieving such an aim may be difficult as urban areas densify (Dallimer *et al.* in press) and domestic gardens are built upon (Goode 2006). Nonetheless, such a strategy to mitigate carbon emissions may be more positively received by the general public than many other approaches to decrease emissions (e.g. to reduce domestic energy use or reliance on car transport within the city) and thus may be readily encouraged. In addition, if current building regulations (DCLG 2006) were amended to improve tree coverage on residential land by planting and, more importantly, protecting trees already in place when constructing new developments, the present carbon pool could be significantly augmented.

Our study comes at a time when the UK government has recently set a target of an 80% reduction in greenhouse gas emissions, from 1990 levels, by 2050 (Great Britain 2008). Local authorities are therefore central to national efforts to cut carbon emissions, although reductions required at city-wide scales are yet to be set. This has led to a need for reliable data to help establish and underpin realistic carbon emission targets and reduction trajectories, along with acceptable and robust policies for meeting these goals. Here, we have illustrated the potential benefits of accounting for, mapping and appropriately managing above-ground vegetation carbon stores, even within a typical densely urbanized European city.

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Supporting Information

Additional Supporting Information may be found in the online version of this article.

Fig. S1. Images illustrating: (a) heterogeneity in landcover across the city of Leicester, as reflected in four 1 × 1 km areas (images © Bluesky International and © Infoterra 2006); (b) examples of high tree densities occurring within *Tree* landcover patches.

Fig. S2. (a) The frequency of surveyed trees in different height classes; (b) the biomass associated with surveyed trees in different height classes. Numbers on the x-axis indicate the upper bound of each height class.

Table S1. The tree species and genera identified during the vegetation survey, the landcover categories where they occurred and the source(s) of the allometric equations applied to surveyed trees. Landcover categories are indicated as follows: T, *Tree*; TS, *Tall Shrub*; S, *Shrub*; G, *Domestic Gardens*.

Table S2. Statistical differences in carbon density within landcover categories, but between different types of land ownership (*Mixed* and *Public*), assessed using z-tests.

Table S3. Statistical differences in carbon density between landcover categories, assessed using z-tests.

Table S4. A summary of the number and diversity of trees surveyed within the different landcover categories.

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