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Land cover in single-family housing areas and how it correlates with urban form

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Abstract Land cover composition is a valuable indicator of the ecological performance of a city. Single-family housing areas constitute a substantial part of most cities and may as such play an important role for sustainable urban development. From aerial photos we performed detailed GIS-based mapping of land cover in three detached single-family housing areas in Denmark of different urban form but comparable housing densities (ranging from 10.0 to 11.3 houses per hectare). The findings were subjected to statistical analysis and landscape metrics. Land cover varied with urban form: A traditional spatial configuration with rectangular parcels contained significantly more vegetation and less impervious surfaces per parcel than newer Radburn-inspired configurations with more quadratic parcels. Correlation analysis showed size of paved access ways to be positively correlated with distance from road to carports in all parcels, and number of trees to be positively correlated with garden size in rectangular parcels. Correlation analysis also showed that higher trees were located further from houses, and that rectangular parcels could support more trees than quadratic parcels. These results suggest that the urban form of neighbourhoods to some degree predicts the long term land cover composition. We conclude that strategies for maximizing the ecological performance of single-family housing areas can be informed by knowledge on urban form, and that digital mapping of land cover based on aerial photography is a useful tool.

Keywords Residential · Detached houses · Gardens · Urban land cover · Urban vegetation · Imperviousness

Introduction

Cities of today are characterized by a land cover composition dominated by constructed impervious surfaces. A high quantity of impervious surfaces affects urban ecosystems at

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multiple scales (Grimm et al. 2008; Pauleit and Duhme 2000; Pauleit et al. 2005), including impairment of wildlife due to loss and fragmentation of habitats (Forman 1995; Gilbert 1991); rising air temperatures and creation of urban heat islands (Henry and Dicks 1987; Pauleit and Duhme 2000; Stone and Norman 2006); displacement of the hydrological balance in terms of reduced ground water recharge, impaired water quality, and increased risk of pluvial floods (Grimm et al. 2008; Shuster et al. 2005). However, these negative effects can to some extent be mitigated by urban vegetation, which may provide a range of ecosystem services such as microclimate regulation, stormwater drainage, habitat provisioning, and may in addition provide recreational values (Bolund and Hunhammar 1999; Gilbert 1991; Pauleit and Duhme 2000; Sanders 1986; Whitford et al. 2001). Concordantly, Whitford et al. (2001) state that land cover composition can be used as an indicator of the ecological performance of an area. As the cities' ecological performance have implications for human well-being, the body of research on urban land cover has grown (Al-Kofahi et al. 2012; Conway and Hackworth 2007; Gill et al. 2008; Pauleit and Duhme 2000; Tratalos et al. 2007).

Single-family housing areas have been pointed out as a prevalent land use type across cities in most of the world (Davies et al. 2009; Gaston et al. 2005; Goddard et al. 2010). This is also the case in Danish cities, where detached single-family housing is the most popular type of dwelling (Andersen et al. 2001), and covers approximately 24 % of urban areas according to coarse-scale spatial data from 1997 (Danmarks Miljøundersøgelser et al. 2000). Hence, single family-housing areas, and their ecological performance are of vital importance to the overall ecological performance of a city (Davies et al. 2009).

Compared to other urban land-use types, single-family housing areas are generally associated with a large quantity of vegetated areas (Attwell 2000; Gill et al. 2008; Pauleit and Duhme 2000). An investigation of the vegetation cover in two Danish towns observed the single-family housing areas to have larger vegetation cover compared to other types of residential areas (Attwell 2000). Similarly, Pauleit and Duhme (2000) observed that single-family housing areas in Munich had the lowest share of impervious surfaces compared to denser residential, commercial and industrial areas, and correspondingly the largest proportion of vegetation. This resulted in comparable lower surface temperatures, higher infiltration rates and less surface runoff. After these studies, the potential ecological importance of gardens in such areas has been acknowledged by researchers across the world (Cook et al. 2012; Davies et al. 2009; Doody et al. 2010; Gaston et al. 2005; Goddard et al. 2010; Rudd et al. 2002; Troy et al. 2007; van Heezik et al. 2013), and several studies have tried to identify factors affecting land cover composition, most of all tree cover, in gardens (Boone et al. 2010; Gaston et al. 2005; Kim and Zhou 2012; Loram et al. 2008; Lowry et al. 2012; Mathieu et al. 2007; Smith et al. 2005; Stone 2004). Social factors, such as socioeconomic status, have been especially investigated, while less focus has been paid to physical factors related to the built environment (Lowry et al. 2012).

On city level, urban form, i.e. the spatial pattern of urban features such as buildings, roads and sidewalks, has been known to affect land cover composition between urban zone and thus the ecological performance (Alberti 2005; Conway and Hackworth 2007; Sanders 1984; Tratalos et al. 2007). Some studies point to physical factors like size and shape of gardens, which are related to urban form, to affect land cover at garden scale (Loram et al. 2008; Lowry et al. 2012; Smith et al. 2005; Stone 2004). Hence, a difference in urban form of single-family housing areas would assumedly result in a difference in land cover composition at neighbourhood scale.

The urban form of single-family housing areas in Denmark is strongly related to the era in which they were built, and distinct typologies exist today (Lind and Møller 1996). Despite the clear difference in urban form, there is a lack of knowledge whether different typologies are characterized by different land cover compositions. Hence, the aim of this study was to feed into the discussion of the ecological potential of single-family housing areas by providing detailed knowledge of land cover composition at both garden and neighbourhood scale in areas of different urban form. A better understanding of land cover composition in single-family housing areas can help planners and policy makers improve the ecological performance of future as well as of existing areas. Knowledge of land cover in existing typologies can provide a basis for developing strategies for climate adaptation and overall sustainable development by mapping out present ecological potentials and challenges, i.e. in terms of space available for habitat provisioning and storm water management. Even small scale land cover types can create differences in the ecological performance of gardens (Davies et al. 2009). Hence, detailed mapping of land cover, which today can be easily obtained from aerial photographs, provides valuable ecological information. Additionally, detailed information provides insight into garden culture and may inform strategies for involvement of garden owners in increasing the ecological performance of their neighbourhood. The study attempted to bridge the gap between city level studies of land cover in urban zones (Attwell 2000; Pauleit and Duhme 2000) and studies of individual gardens (Gaston et al. 2005; Loram et al. 2008; Smith et al. 2005).

Based on aerial photographs a detailed mapping of the land cover in three typologies of detached single-family housing areas in suburban Copenhagen, Denmark, was made. Statistics were used to test for (1) similarities and differences in land cover extent between typologies, and (2) correlations between selected land covers and spatial features related to urban form within typologies. Furthermore, landscape metrics from landscape ecology, which Kim and Zhou (2012) and Robinson (2012) demonstrated to be applicable at block and parcel level, were used to analyse the spatial configuration of tree cover.

Methods

Study sites

The three sites to be selected should vary from each other in urban form i.e. the patterns of roads, parcels and houses, but otherwise be comparable, which means that in addition to similar housing density the three sites should meet the following criteria:

1. The sites should be situated relatively close together in order to prevent regional variations in garden culture and thus land cover (Ravn 2011). This criterion was also based on the general assumption within geography that near things are closer related than things further apart (Tobler 1970).
2. The sites should be developed on land previously used for agriculture, and there should be no forest. This criterion was to ensure that the origin of the present vegetation was post-development and not remnant or emergent vegetation influenced by an existing or neighbouring forest (Zipperer et al. 1997). It also assured a more comparable hydrology of the sites as it leaves out previous meadows and wetland etc., which could have influenced the growth conditions.
3. The terrain of the sites should be gentle, as steep slopes could affect the growth conditions.

4. There should be no spectacular views from the sites, as this could influence the willingness of parcel owners to allow taller land cover types such as trees.
5. The socioeconomic status should be similar.

The resulting study sites are shown in Fig. 1, and referred to as site A, B, and C. All sites were located in the western suburbs of Copenhagen, Denmark, with a maximum distance between sites of 5.2 km, all developed on previously agricultural land on gently sloping terrain with no spectacular views. Socioeconomic status was assumed to be relatively similar according to information about the sites' two municipalities (StatBank Denmark 2013).

The three sites are from different time periods. Site A is characteristic of the period when areas with detached housing started to emerge in the beginning of the 20th century; it is dominated by straight roads and narrow, rectangular parcels with quadratic houses facing the road. Narrow parcels made it possible to have many parcels along a single road. The houses were built close to the road to minimize the length of pipelines and to ensure space for vegetable plots in the rear garden. Site B is characteristic of the next period, which began around 1960, where a strict and separated traffic system with cul-de-sacs became popular, and new types of houses called for quadratic parcels to ensure maximum sun exposure of houses and gardens. Privacy and free space around the house were more important than space for vegetable plots. In this period, which in Denmark was dominant in the 1960's and 1970's, most single-family houses were built, and the characteristic urban form of site B is often referred to as "a Radburn" based on the planning of Radburn, New Jersey (Lind and Møller 1996). Site C is a newer version of "a Radburn" as the form gradually evolved to have more irregular street patterns and parcel shapes during the 1980's and 1990's in Denmark. Though the sites are not representative for the population of single-family housing areas, they are assumed to represent urban forms that can be found in most towns across the world with the traditional form of site A being most prevalent worldwide and located closer to city centres than the newer forms represented by site B and site C.

The delineations of the sites (red lines in Fig. 1) are based on district plans, with the following notifications: Site A is delineated by the centre lines of adjacent roads; site B is delineated to the east and south by the centre lines of adjacent roads. For site C it should be noted that the road leading to other housing areas has been extracted from the site including the verges. A general characterisation of the three study sites is provided in Table 1.

Data collection

All area in the three sites was categorized after land cover types (Table 2). In total 31 different land cover types were assigned, ranging from different types of impervious covers, over different types of vegetative cover to a number of special cover types. To make comparisons easier, the land cover types were grouped into three classes (impervious, vegetation, other), or even sub-classes, and a distinction was made between common and private land covers as shown in Table 2.

Information on land cover type was obtained by visual interpretation of aerial photographs with a resolution of 12.5 cm (COWI, 12.5 cm, 2010), followed by manual digitization in ArcGIS 10.0. Tree height was estimated based on length of shadows. Street photos from Google Street View and oblique aerial photographs supported the interpretation. To keep the judgement consistent only one person (the first author) undertook the visual interpretation of land cover types and tree height for all three study sites (Gill et al. 2008; Heywood et al. 2006).

Fig. 1 Aerial photographs of the single-family housing areas in the study. The *red line* delineates the three sites. *Top*: Site A, 'Traditional', from 1950s. *Middle*: Site B, 'Radburn', from 1960s. *Bottom*: Site C, 'Modified Radburn', from 1990s

Spatial data on parcel boundaries and year of construction of houses came from an existing database from 2010 from the Danish National Survey and Cadastre (Table 1). Parcel size and location were calculated in ArcGIS based on the spatial data from this database, while length

Table 1 General characterisation of site A, B, and C. Data origins from existing databases

	Unit	A	B	C
Year of construction of houses	Median	1953	1966	1998
	Range	1950–1962 (2010)	1965–1973	1997–1998
Number of parcels	integer	96	73	75
Total area	m^2	88 910	64 572	75 027
Common areas of total area[a]	%	15	20	23
Private parcels of total area	%	85	80	77
Housing density	Houses per ha	10.8	11.3	10.0
Total area per parcel	m^2	926	885	1000
Mean parcel size	m^2	788.8±85.5	707.2±19.4	774.4±82.6
Mean depth of parcel	m	40.1±0.2	27.2±2.1	28.6±4.2
Mean width of parcel	m	19.7±2.1	26.0±2.5	27.5±3.7
Mean depth to width ratio		2.05±0.17	1.1±0.2	1.1±0.3

[a] Common areas refer to areas owned commonly be the owners of the parcels. Such areas are publically accessible but typically only used by the residents of the site

and width of parcels were measured in ArcGIS. Distance from road boundary to carports and garages was measured perpendicular to the boundary to test for correlation with size of access ways. The proximity analysis "Near" in ArcGIS 10.0 was used to calculate distance from a tree to a house.

The spatial pattern of tree cover can affect ecological processes in a range of ways (Forman 1995); hence, the descriptive data of tree cover extent and proportion was supplemented with calculation of landscape metrics. To characterize spatial pattern of tree cover, sub-classes with plantings higher than 3 m in common and private areas were converted to raster format and exported to Fragstats 'spatial pattern analysis program' ver. 4.0 (McGarigal et al. 2012) for calculation of landscape metrics. Six landscape metrics were calculated to examine aspects of fragmentation, aggregation, isolation and connectivity, see further description in Table 3. Calculations were performed both with and without including common trees to investigate their importance for the spatial pattern. The selection of metrics was based on the study by Kim and Zhou (2012).

Statistical analysis

Two sample Wilcoxon tests were used to test the following differences in land cover between sites: (1) mean area per parcel, (2) mean percentage of parcel area, (3) and mean percentage of garden area. Land covers with a mean frequency of less than 15 % were not tested.

Spearman's rank correlation (r_s) was used to test for correlations between the following: (1) size of access ways and distance from road boundary to carports or garages, (2) number of trees and parcel size, (3) number of trees and garden size, and (4) tree height and distance from a tree to a house. Analysis 1 only included parcels with carports or garages. The Spearman's rank correlation method only tests if the variables are correlated and does not assume any causal relationships.

In all analyses a significance level (p-value) of 0.05 was used. The analyses were carried out in R Statistical Software.

Table 2 Land cover classification

Class	Sub-class	Land cover type	Description
Common land covers			
Impervious	Roads	Road	Asphalted road
	Paved areas	Sidewalk	Paved sidewalk
		Path	Paved or asphalted cycle and walking paths
		Parking area	Asphalted parking area
Vegetation	Grass	Grass	Common lawn
	Plantings < 0.5 m	Planting bed	Common flower beds, ground covering perennials and bushes no higher than 0.5 m
	Plantings 0.5–3 m	Bushes	Common bushes and small trees with a height of 0.5–3 m
	Plantings > 3 m	Tree cover[a]	Canopies of common trees and large bushes > 3 m
Other		Loose surface	Gravel, pebbles and shingles used on accessible areas such as paths
		Loose ground cover	Gravel, pebbles and shingles used as ground cover in beds
Private land covers			
Impervious	Roofs	Roof	Roofs of main buildings
		Extension roof	Roofs of house extensions like carports and sheds
	Paved areas	Access way	Paved driveways, paths to front doors and garden paths
		Terrace	Paved outdoor areas, often adjacent to the house
Vegetation	Grass	Grass	Lawns. Grass covered by movable equipment such as trampolines was included
	Plantings < 0.5 m	Planting bed	Flower beds, ground covering perennials and bushes lower than 0.5 m
		Vegetable plot	Beds with plants in straight lines and bare soil
	Plantings 0.5–3 m	Bushes	Bushes and small trees with a height of 0.5–3 m
		Climbing plant	Climbing plants covering roofs, walls, fences and pergolas.
		Hedge	Coherent lines of bushes of similar appearance
	Plantings > 3 m	Tree cover[a]	Canopies of trees and large bushes > 3 m
Other		Green house	Green houses
		Fence	Fences, free standing walls

Table 2 (continued)

Class	Sub-class	Land cover type	Description
		Wooden deck	Wooden decks
		Loose surface	Gravel, pebbles and shingles used on accessible areas such as driveways and paths
		Loose ground cover	Gravel, pebbles and shingles used as ground cover in beds
		Bare soil	Bare soil
		Pond	Garden ponds with visible water surface
		Swimming pool	Permanent swimming pools. Including above ground swimming pools.
		Other feature	Features not relevant for this study
		Unidentified	Features that could not be accurately identified

Only the top land cover was mapped. Hence, grass underneath tree cover would not be registered as grass

[a] The canopies of trees planted in common areas and overlapping private parcels were categorised as common tree cover

Table 3 Landscape metrics used in this study

Metric	Description	Unit	Range	Aspect of landscape pattern
Percentage of landscape (PLAND)	The percentage of the landscape comprised of the corresponding patch type.	Per cent	$0 < \text{PLAND} \leq 1$	Abundance
Patch density (PD)	Number of patches in the corresponding patch type per 100 ha.	Number per 100 ha	$0 \leq \text{PD}$	Fragmentation
Mean patch size (MPS)	Mean area of patches in the corresponding patch type	Hectares	$0 < \text{MPS}$	Fragmentation
Normalized landscape shape index (nLSI)	Measure of aggregation. 1 is when the patch type is maximally disaggregated	None	$0 \leq \text{nLSI} \leq 1$	Aggregation
Euclidean nearest-neighbour distance (ENN)	Mean distance between the focal patch and its nearest neighbour of the same class using simple Euclidean geometry as the shortest straight-line distance.	Meters	$0 < \text{ENN}$	Isolation
Correlation length (CL)	The distance that one might expect to traverse the map while staying in a particular patch, from a random starting point and moving in a random direction.	Meters	$0 < \text{CL}$	Physical connectedness

Results

Characteristics at site level

Figure 2 shows the distribution of vegetation (green) and impervious (grey) land covers in the three sites, on both private and common land. The distribution of sub-classes can also be seen from Fig. 2. Finally, Fig. 2 depicts a miniature diagram of road, parcel, and house pattern of each site. The total area used per parcel can be seen in Table 1.

Site A with its rectangular parcels and straight roads contained more vegetation than the more quadratic parcels with cul-de-sacs of site B and C, measured both in m^2 per parcel and in percentage of whole site. Although site C had only slightly less vegetation per parcel than site A, a large difference existed in the composition in that site C was more dominated by grass and had less tree cover than site A (Fig. 2). As much as 63 % of the vegetated area in site C was covered by grass, while the proportion was 43 % in both site A and B. Both site B and C had common trees; still the total tree cover was largest in site A with no common trees (Fig. 2, Table 4). Site A had 27 m^2 more tree cover per parcel compared to site B and 94 m^2 more compared to site C.

The results from the landscape metrics showed that patches of tree cover in site A compared to site B and C were most abundant (PLAND), least fragmented (PD and MPS), most aggregated (nLSI), least isolated (ENN), and most physically connected (CL) (Table 4). The analyses excluding common tree cover in site B and C showed a lower abundance (PLAND) and a higher isolation of patches (ENN), while the mean patch size (MPS) and correlation length (CL) increased (Table 4). Hence, patches of common tree cover were smaller than patches of private tree cover, but added to the connectivity in the sites.

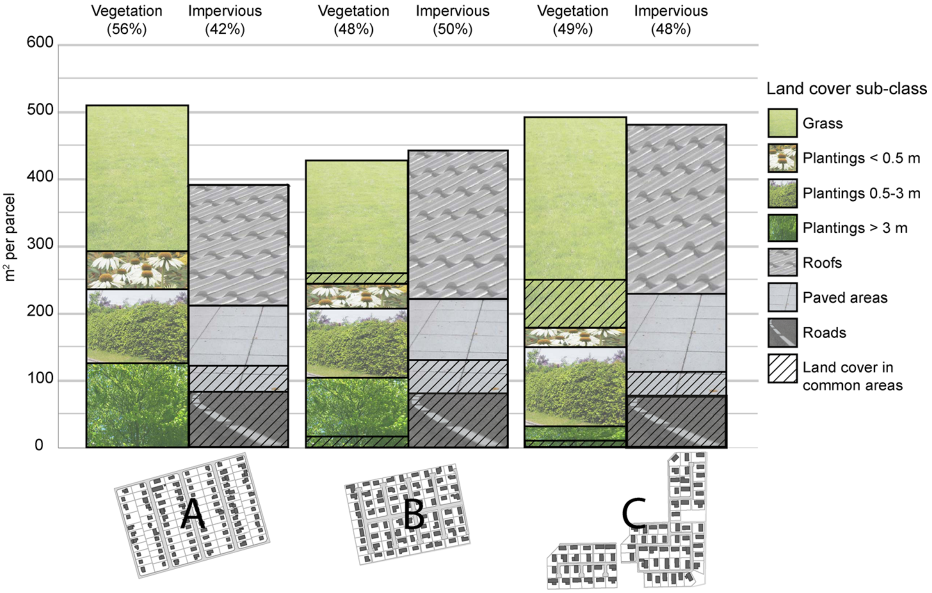

Fig. 2 Vegetation and impervious land covers in common areas and private parcels in m^2 per parcel. *Note*: The areas with common plantings < 0.5 m in site B and common plantings 0.5–3 m in site C were too small to be visible in the figure. The land cover class "Other" is not shown

Table 4 Landscape metrics of site A, B, and C. For site B and C the metrics are calculated both with and without (in italics) common trees

Site	Percentage of landscape (PLAND)	Patch density (PD)	Mean patch size (MPS)	Normalized landscape shape index (nLSI)	Euclidean nearest-neighbour distance (ENN)	Correlation length (CL)
A	13.67	3263.71	0.0042	0.1679	4.37	5.03
B	11.31	3406.63	0.0033	0.1860	4.47	4.19
B	*9.80*	*2725.30*	*0.0036*	*0.1792*	*5.21*	*4.23*
C	3.30	2570.45	0.0013	0.2833	7.36	2.07
C	*2.36*	*1744.71*	*0.0014*	*0.2761*	*8.21*	*2.10*

Site C had the highest quantity of impervious surfaces per parcel, but the total percentage of impervious surface was slightly larger in site B (Fig. 2). Site A had the lowest quantity of impervious surfaces, and Fig. 2 shows that the differences were caused mainly by the quantity of private impervious surfaces. Further details on common and private land cover will be presented in the following sections.

Characteristics of common area

Impervious surfaces

The common areas were mainly covered by asphalted roads (Table 5). In site A and B the road area per parcel was relatively similar, while site C had a lower quantity (Table 5, Fig. 2). The

Table 5 Land cover in common areas of site A, B, and C. Expressed as m^2 per parcel

	A	B	C
Size of common area	137	177	226
Impervious areas	122.8	130.4	114.0
Asphalt road	81.7	80.2	75.9
Paved sidewalk	41.1	21.6	14.4
Bicycle and walking path (paved or asphalted)	0	10.1	23.7
Asphalt parking area	0	18.5	0
Vegetation cover	14.3	46.2	100.3
Grass	0	15.8	63.4
Grass reinforcement	0	0	8.2
Common tree cover	0	13.4	9.0
Private tree cover[a]	5.7	4.6	1.2
Bushes	0	0	0.4
Private bushes and hedges[a]	8.6	11.0	18.1
Planting beds	0	1.4	0
Other land cover	0	0.4	10.6
Loose surface	0	0	10.6
Loose ground cover	0	0.4	0

[a] Overlapping common areas

difference reflects a disparity in width of local roads, as the width was only 4.5 m in site C, and 6 m and 5.5 m in site A and B respectively. Large differences were observed in the quantity of paved sidewalks, with site A having twice the area per parcel than site B, and almost three times the area of site C. Only one side of the roads at site C was equipped with sidewalks. Both site B and C had a separate bicycle and pedestrian path system, which added to the quantity of impervious surfaces in the sites, as did the paved parking areas along the roads at site B (Table 5).

Vegetation

There were considerable differences in the quantity of common areas designated for vegetation, ranging from none in site A to considerable quantities in site C. In site B and C the vegetation consisted of mainly grass and trees. The area of grass in common areas was considerably larger in site C than B (Table 5, Fig. 2). In site B, all grass cover consisted of narrow areas along the main road, whereas larger and coherent grass areas were found in site C, along with such facilities as tables and benches and football goals. All common trees in site B and C were located along the roads. The greatest number of common trees occurred in site C (trees per parcel: B: 0.5, C: 0.8). Nevertheless, the cover of common trees was largest in site B (Table 5), where most of the trees also appeared to be older.

Characteristics of private parcels

Site A had the smallest percentage of total impervious surfaces on parcels while site C had the largest (Table 6). Accordingly, the total vegetation cover was largest in site A and lowest in site C, and the land cover class "other" was also largest in site A. Selected findings for individual land cover types are described below.

Impervious surfaces

Site C contained the largest quantity of impervious surfaces per parcel and in percentage of parcel area, but the percentage of garden area did not differ significantly from site B (Table 6). A large part of the impervious surfaces consisted of roofs in all three sites (Table 6, Fig. 2). The size of roofs explains much of the observed differences in impervious surfaces since approximately 2/3 of the houses in A had 1.5 stories, which were also the oldest and smallest houses, while the remaining houses in all three sites were larger one-storey houses.

Site C had the largest quantity of paved access ways and paved terraces. The area of paved terraces of site A was also quite high, and did not differ significantly from site C (Table 6). The narrow parcels in site A contained the smallest quantity of access ways (Table 6). Results from the correlation analysis between size of access ways (Table 6) and distance from road boundary to carports are shown in Table 7. There was a significant correlation in all three sites, meaning that parcels with a longer distance from the road to a carport had a larger quantity of paved access ways.

Vegetation

The area covered by vegetation in site A varied significantly from site B and C with at least 100 m^2 more vegetation cover per parcel in site A on average (Table 6). It should be noted that

Table 6 Land cover on private areas of site A, B, and C. Expressed as frequency of occurrence (%), total area (m^2 per parcel), and proportion of parcel and garden area (%)

	Site A				Site B				Site C			
	Freq. %	Area per parcel Mean	% of parcel Mean	% of garden Mean	Freq. %	Area per parcel Mean	% of parcel Mean	% of garden Mean	Freq. %	Area per parcel Mean	% of parcel Mean	% of garden Mean
Garden size		668.5±97.3	84.6±5.2	–		542.1±31.2 a	76.7±3.9	–		564.9±78.6 a	72.8±4.4	–
Total impervious		269.6±66.2	34.6±9.4	22.8±8.7		311.4±50.5	44.0±6.9	27.0±7.7 a		364.8±58.2	47.2±5.9	27.5±6.7 a
Roof	100	120.4±37.7	15.5±5.2	–	100	165.1±28.5	23.4±3.9	–	100	209.4±35.8	27.2±4.4	–
Extension roof	99.0	59.1±29.0 a	7.6±3.9 a	9.0±4.5 a	100	57.2±20.7 a	8.1±3.0 a	10.6±3.8	96.0	42.9±19.7	5.5±2.4	7.6±3.3 a
Paved areas	99.0	90.2±43.0 a	11.5±5.6 a	13.8±7.1	100	89.1±33.9 a	12.6±4.7 a	16.5±6.3	100	112.5±37.2	14.5±4.3	19.9±5.9
Access way	96.9	46.3±27.3	6.0±3.6	7.2±4.5	100	53.9±22.9	7.6±3.2 a	9.9±4.1 a	100	62.7±28.1	8.1±3.6 a	11.2±5.0 a
Terrace	94.8	43.8±29.3 a	5.5±3.6 ab	6.7±4.6 a	95.9	35.3±24.6	5.0±3.5 a	6.5±4.6 a	98.7	49.8±28.9 a	6.4±3.5 b	8.7±4.7
Total vegetation		498.2±115.8	62.8±10.5	74.0±10.4		386.2±52.9 a	54.6±7.5	71.2±8.7 a		398.2±71.2 a	51.4±6.6	70.5±7.5 a
Grass	100	218.1±73.8	27.6±8.7	32.8±10.5 a	100	170.6±60.6	24.1±8.4	31.3±10.5 a	100	242.5±67.5	31.3±7.7	42.8±9.8
Planting bed	92.7	44.6±33.4	5.6±4.2	6.7±5.0 a	87.7	30.0±26.2 a	4.3±3.7 a	5.6±4.9 ab	90.7	25.5±24.5 a	3.3±3.1 a	4.5±4.5 b
Vegetable plot	32.3	12.4±25.0	1.6±3.2 a	1.9±3.7 a	19.2	5.3±12.8 b	0.8±1.8 ab	1.0±2.4 ab	18.7	4.1±9.3 b	0.6±1.2 b	0.7±1.7 b
Bushes	94.8	55.0±43.8 a	6.9±5.6 a	8.1±6.4 ab	100	55.0±39.8 a	7.8±5.7 a	10.2±7.4 a	98.7	34.8±24.0	4.5±3.0	6.2±4.1 b
Climbing plant	18.8	0.9±2.6 a	0.1±0.4 a	0.1±0.5 a	37.0	2.3±4.8	0.3±0.7	0.4±0.9	10.7	0.5±1.7 a	0.1±0.2 a	0.1±0.3 a
Hedge	100	46.2±23.5	5.8±2.8 a	6.9±3.3 a	96.0	36.3±22.9	5.1±3.2 a	6.7±4.1 a	100	64.8±17.3	8.3±2.0	11.5±2.8
Tree cover	97.9	121.1±82.6	15.1±9.8	17.5±11.0 a	97.3	81.8±55.7	11.6±7.9	15.1±10.3 a	82.7	22.5±24.3	3.0±3.4	4.1±4.6
Common bushes[a]	–				5.5	0.6±3.1	0.1±0.4	0.1±0.6	–			
Common trees	–				26.0	4.4±9.3 a	0.6±1.3 a	0.8±1.7 a	40.0	3.5±6.4 a	0.4±0.7 a	0.6±1.0 a
Total other		21.2±26.1	2.7±3.3	3.2±3.9		11.1±16.0 a	1.6±2.3 a	1.9±2.9 a		11.4±14.9 a	1.4±1.9 a	2.0±2.7 a
Green house	33.3	3.2±5.0	0.4±0.6	0.5±0.8	15.1	1.2±3.2 a	0.2±0.5 a	0.2±0.6 a	6.7	0.6±2.4 a	0.1±0.3 a	0.1±0.4 a
Fence	56.3	3.7±5.6 a	0.5±0.7 a	0.6±0.9 a	58.9	3.4±4.7 a	0.5±0.7 a	0.6±0.9 a	25.3	1.5±2.8	0.2±0.4	0.3±0.5
Wooden deck[a]	7.3	1.9±7.9	0.2±1.0	0.3±1.1	2.7	0.4±2.6	0.1±0.4	0.1±0.5	4.0	0.4±6.6	0.2±0.9	0.3±1.3
Loose surface[a]	21.9	6.1±15.4	0.8±1.9	0.9±2.1	5.5	0.9±4.0	0.1±0.6	0.2±0.7	4.0	2.2±7.0	0.3±1.0	0.2±1.3
Loose ground cover[a]	5.2	0.7±4.4	0.1±0.6	0.1±0.7	6.8	1.6±7.5	0.2±1.1	0.3±1.4	16.0	2.2±6.4	0.3±0.8	0.4±1.2

Table 6 (continued)

	Site A				Site B				Site C			
	Freq. %	Area per parcel Mean	% of parcel Mean	% of garden Mean	Freq. %	Area per parcel Mean	% of parcel Mean	% of garden Mean	Freq. %	Area per parcel Mean	% of parcel Mean	% of garden Mean
Bare soil[a]	6.3	1.5±6.9	0.2±0.9	0.2±1.1	6.8	1.8±10.1	0.3±1.5	0.3±1.8	6.7	0.6±2.4	0.1±0.3	0.1±0.5
Pond[a]	–				1.4	0.2±1.7	0.0±0.2	0.0±0.3	1.3	0.0±1.7	0.0±0.2	0.0±0.3
Swimming pool[a]	1.0	0.3±3.1	0.0±0.4	0.1±0.5	–				2.7	1.2±7.3	0.1±0.8	0.2±1.2
Other feature[a]	25.0	3.5±12.1	0.5±1.5	0.5±12.1	11.0	0.8±2.5	0.1±0.4	0.1±0.5	32.0	2.6±5.0	0.3±0.6	0.5±0.9
Unidentified[a]	1.0	0.3±3.3	0.1±0.5	0.1±3.3	5.5	0.7±3.5	0.1±0.5	0.1±0.6	1.3	0.4±3.0	0.0±0.4	0.1±0.5

Land cover types are private, unless stated otherwise. Note: Two sample Wilcoxon tests showed no significant differences among means with the same letter: i.e. a and b

[a] Land cover means were not tested for differences

Table 7 Correlation between access way per parcel (m^2) and distance from road to carports and garages (m)

Site	A	B	C
Mean distance to carport	7.5±6.3 a	10.7±6.4 b	9.7±7.0 ab
Spearman rank correlation (r)	0.51***	0.45***	0.62***
Number of observations	81	68	72

Significance levels are shown by asterix: 0 *** 0.001 ** 0.01 * 0.05

Two sample Wilcoxon tests showed no significant differences among means with the same letter: i.e. a and b

the mean garden size was more than 100 m^2 larger in site A than in site B and C, and most vegetation land covers that differed significantly between site A and B in extent and proportion of parcel did not differ significantly in proportion of garden area.

Clear differences between the three sites were observed with respect to private trees. Some tree cover from private trees was found on nearly every parcel in site A and B, while almost one-fifth of the parcels in site C had no tree cover at all (Table 6). Correspondingly, there were significant differences in tree cover, both in absolute numbers per parcel and in percentage of parcel area, with site A parcels having in average 121.1 m^2 covered by trees, while the corresponding numbers for site B and C are 81.8 m^2 and 22.5 m^2, respectively (Table 6, Fig. 2).

Figure 3 shows the number of trees per parcel in the three sites, with the significantly largest mean in site A and the lowest mean in site C. In site A, there was one tree for every 119.5 m^2 of garden area, while there was one tree for every 128.5 m^2 in site B and for every 249.2 m^2 in site C. Correlation analysis showed a positive correlation between number of trees and both garden and parcel size in site A (garden size: $r_s=0.41$, $p<0.001$; parcel size: $r_s=0.26$, $p=0.010$) whereas no significant correlations were found in site B (garden size: $r_s=-0.11$, $p=0.35$; parcel size: $r_s=-0.12$, $p=0.31$) and C (garden size: $r_s=0.13$, $p=0.25$; parcel size: $r_s=0.05$, $p=0.65$).

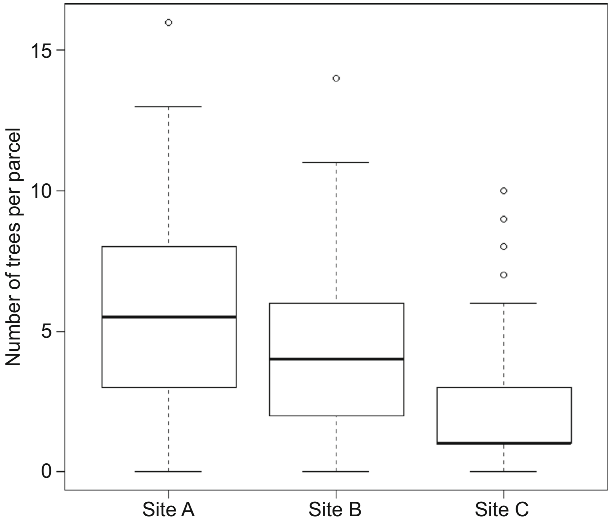

Fig. 3 Boxplot of number of trees per parcel

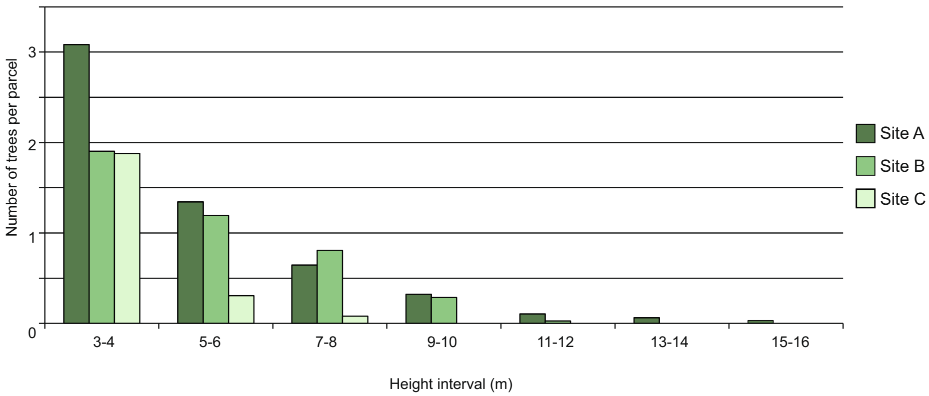

Fig. 4 Number of trees per parcel in the three sites, after height (intervals of 2 m)

The mean number of trees per parcel within certain height intervals is illustrated in Fig. 4. The highest trees were found in site A, which was the only site with trees in the interval of 13–16 m. Approximately 1.7 % of all the trees in site A were this tall. The highest trees in site B were 11–12 m, while the highest trees in site C were only 7–8 m. Site A had a mean of more than 3 trees per parcel with a height of 3–4 m, while site B and C had less than 2 trees per parcel this size. Correlation analysis in site A and B indicated that higher trees were located further from houses than smaller trees (Table 8).

In correspondence with lack of trees, most grass per parcel was found in site C (Table 6). In average the site C parcels had 72 m^2 more grass compared to site B, and 24 m^2 more compared to site A (Table 6, Fig. 2).

Hedges were present on most parcels, except a few in site B (Table 6). The mean area of hedge cover differed between all three sites with the largest mean in site C, where the use of fences was less prevalent (Table 6). Vegetable plots and planting beds occurred more frequently and covered a larger area in site A than in site B and C (Table 6).

Other land covers

The largest frequency of greenhouses was found in site A and the lowest in site C. Two other land covers were found more often in one area than in the other two. These were areas with pebbles, gravel or shingles used as accessible areas, such as access ways, and inaccessible areas, such as ground cover in beds (Table 6). Garden ponds and swimming pools only occurred rarely.

Table 8 Correlation between height of trees (m) and distance from a tree to a house (m)

Site	A	B	C
Mean distance to house	8.9±5.6	6.0±3.1 a	5.9±3.2 a
Spearman rank correlation (r)	0.12**	0.13*	0.06
Number of observations	537	308	170

Significance levels are shown by asterix: 0 *** 0.001 ** 0.01 * 0.05

Two sample Wilcoxon tests showed no significant differences among means with the same letter: i.e. a and b

Discussion and conclusions

The method of manually mapping land cover in ArcGIS generated a high level of accuracy that even revealed differences in land covers with a small extent like shingles, vegetable plots, hedges and individual trees. Although the method is time-consuming, it returns more detailed information than methods employed in other studies (Akbari et al. 2003; Mathieu et al. 2007; Pauleit and Duhme 2000; Pauleit et al. 2005), and is still less time-consuming than mapping by visits in the field (Loram et al. 2008; Smith et al. 2005). Although field mapping allows for smaller features and multiple overlapping land covers to be included, this method is restricted to mapping gardens to which the investigators have the owner's approval, and thus it would be difficult to obtain information about entire neighbourhoods. Where the sites have never been visited, the method used in this study can be easily applied and potentially modified, depending on the purpose, to another level of detail or only focus on certain land covers to make it less time-consuming.

Since the choice of the three study sites were based on differences in urban form, rather than random sampling, no attempt was made to transfer the results to the whole population of single-family housing areas in Denmark or Europe. In fact, the results highlight the need for recognizing differences in urban form when estimating land cover composition and the related ecological performance of single-family housing areas. The study showed differences in land cover composition of three different urban form typologies. Hence, strategies for maximizing the ecological performance of these predominant areas in our cities can be informed by knowledge on urban form. To further inform such strategies the descriptive data reported in this study can be combined with methods used in literature (Whitford et al. 2001) to calculate indicators for the ecological performance in single-family housing areas.

On neighbourhood level the greatest differences were found in quantity of impervious surfaces, tree cover, bed cover, and grass cover, where the traditional layout of site A clearly presented the largest ecological performance based on the lower quantity of impervious surfaces and the higher quantity of vegetation and especially tree cover (Fig. 2). Besides land cover composition, the traditional layout additionally demonstrated an advantageous spatial configuration of tree cover for wildlife distribution and habitat (Table 4). The results feed into the hypothesis that the ecological footprint can be reduced and ecosystem services increased through urban form.

A main reason for the difference in land cover composition at neighbourhood level was the land cover on private parcels, where parcels in site A had the largest quantity of tree cover, the smallest house footprint, and the smallest access ways. We suggest that the differences in access way area were due to a combination of spatial configuration and garden trends at time of development. The spatial configuration with narrow parcels and houses close to the road in the traditional layout of site A left little space for broad driveways as driveways and carports were often situated in the limited space next to the house.

The results indicated that garden trends also have an impact, which is seen in the 1990s site (site C) that was built during a time where paved areas increased in private gardens due to garden trends (Perry and Nawaz 2008; Verbeeck et al. 2011). Part of the reason for the increasing size of driveways in the period was that it had become common to own more than one car (Perry and Nawaz 2008). Although the older sites have gone through the same time period and the residents probably have two cars as well, the driveways have not been enlarged to the same extent. The sites have to some degree been unaffected by the trendsetting changes which influenced the newer developments significantly. The same tendency was seen with the ground cover of shingles in beds, which became popular in the 1990s in Denmark (Ravn 2011), and which occurred far more frequently in the 1990s site (C) than in the other two sites. Vegetable plots represented an opposite trend that was widespread during the development of the oldest site (A). Hence, the garden trends at time of development seemed to have a long lasting impact on land cover, more or less overruling later garden trends. Unfortunately this also means that the spread of good practices from garden to garden, for instance for a more wildlife friendly garden, is likely to be a slow process in established neighbourhoods.

One could suggest that the larger extent of tree cover on the rectangular parcels of the oldest neighbourhood (site A) could be explained simply by age of neighbourhood (Lowry et al. 2012; Talarchek 1990), and the higher trees in site A than in the younger neighbourhoods supported this. However, if this was the only explanation, the number of trees would have been constant despite the age of neighbourhood, which is not the case, in that site A had more trees per m^2 of garden. Rather, we assume that the larger number of trees was related to parcel shape and house location. The fact that the higher trees were located in the far end of the parcels (Table 8) indicated that parcel owners preferred to have trees in some distance of the house, which was also found by Smith et al. (2005). Trees could be further from houses on the rectangular parcels with houses near the road and a large, coherent area of rear gardens than on the quadratic parcels with houses situated in the centre and neighbouring houses close by at all boundaries. Furthermore, correlation analysis within site A showed that the larger parcels and gardens had more trees than the smaller parcels and gardens. A similar correlation did not exist in the other neighbourhoods with more quadratic parcels. Lack of correlation may be because of limited data (too little variation in parcel sizes in site B and too few trees in site C, making the analysis statistically insignificant), or it may be due to the shape of parcels. An increased size of rectangular parcels could add more to the maximum distance from a tree to a house by adding garden area in the rear garden than an increased size of quadratic parcels with houses in the centre where garden area would be added along all boundaries. The later would suggest that a small rectangular parcel would contain as many trees as a larger quadratic parcel.

Hence, the planning of coherent rear gardens in rectangular parcels meant for growing food and the location of houses close to the road for minimizing pipelines has led to unforeseen ecological benefits as well as new one-storey house types, while the attention to privacy and free space around houses that led to square parcels had unintended ecological consequences. However, the focus on traffic safety and reduced speed with cul-de-sacs and bending roads in site B and C allowed for narrower roads and less paved sidewalks. Sidewalks were instead supplemented by a separated path system that assumedly had less ecological impacts as the path system was surrounded by vegetation and partly disconnected from the sewer system.

The findings presented here on relations between parcel shape and size and land cover in gardens may be used to inform planning of new single-family housing areas. Planners are already aware of the possibility of reducing housing footprint by allowing or dictating houses to have two storeys instead of just one, which is seen more and more often in new developments. A simple measure that could decrease the quantity of paved access ways in new areas would be to regulate the distance from road to carport by stating a maximum distance in district plans. Today, many district plans for single-family housing areas in Denmark state a minimum distance from road to carport, but a maximum distance could improve the ecological performance by minimizing imperviousness. Imperviousness can also be reduced by a minimization of road width as seen in site C. Planting of street trees would also add to the connectivity of tree cover, according to the analysis of the spatial structure of tree cover (Table 4), and mitigate some of the negative consequences of impervious surfaces.

The results also indicated that garden trends have impact on land cover, which would be difficult to control through planning, and rather calls for mindset changing through knowledge dissemination (van Heezik et al. 2012). More research in the relationship between typologies of single-family housing areas and the people who live there would help in the understanding of possible planning measures to ensure a high ecological performance.

Though the newest neighbourhood from 1990s (site C) was assessed to have a lower ecological performance due to little tree cover and high imperviousness (Whitford et al. 2001), the large, coherent common areas meant for social activities offer some ecological potential. In their present state they only have minimal positive ecological effects as they mainly consist of grass. Dry grass during the summer is known to enhance the urban heat island effect (McPherson et al. 1989), and woody vegetation plays a larger role as habitat for many vertebrate and invertebrate species (Savard et al. 2000). Nevertheless, the grasslands hold great potential as they could be used for storm water management and transformed into areas with more woody vegetation with benefits for wildlife and urban heat island mitigation. Such potential was lacking in the other two sites, as the common areas were mainly targeted for transportation infrastructure and only smaller parts could be spared for other uses. In these sites more radical changes would be necessary to accommodate stormwater retention and infiltration and enhancement of habitat quality. Either roads, sidewalks or parking areas should be abolished and altered, or private parcels; i.e. people's private gardens, should be altered if eco-structures for benefitting the environment are to be initiated. Future studies could explore the willingness of garden owners to implement wildlife friendly and climate adaption features, as well as test suitability of different eco-features in common areas. New ecological measures must function under the terms of parcel owners, as the main purpose of single-family housing areas is to provide homes and daily recreation for the residents.

The results indicate that cities with a large proportion of older areas of the traditional layout support a large number of ecosystem services as it is; however, in many of such neighbourhoods, unlike the neighbourhood from this study, parcels have been subdivided and garden sizes reduced which affects the ecological performance negatively (Pauleit et al. 2005). The imperviousness would increase and quantity and the connectivity of tree cover would be expected to decrease. Another threat to the ecological performance is the demolition of the original houses and building of new and larger ones. One such example was observed in site A (data not shown) and here proportion of impervious surfaces went up by 20 percentage points compared to the site mean and the proportion of tree cover went down by 14 percentage points. Hence, restrictions on house footprint and protection of existing trees would be supportive in keeping a high ecological performance in case of redevelopment.

This study provided quantitative numbers on land cover that can form a basis for planners' and policy-makers' decisions about where to concentrate the efforts to improve the ecological performance of single-family housing areas to make Danish cities more climate resilient and wildlife friendly, both when planning for new residential areas and when retrofitting existing areas. A mapping of single-family housing areas on the basis of urban form would be beneficial when estimating the present ecological performance and when planning approaches to enhance the performance.

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