Enhancing the Climate Change Benefits of Urban Trees in Cambridge

Abstract

Increases in canopy cover within cities can aid adaptation to the adverse effects of climate change such as an enhanced urban heat island effect, increased harmful radiation, poorer air quality and more flooding. The aim of this project was to produce an evidence base to help develop a targeted tree planting and management strategy to maximise the benefits that urban trees in Cambridge can bring (direct and indirect cooling effects, shelter from harmful radiation and improvement of urban air quality). Spatial analysis techniques were used to quantify the tree density and canopy cover, height and canopy spread distributions in Cambridge by land use, ward and ownership using a digital tree map derived from aerial photography and digital terrain data (ProximiTREE™). Twenty-four 4-hectare plots in Cambridge were selected for ground survey based on a land-use stratification to represent the tree stock distribution by land use in the city. The ground survey was undertaken to provide an estimate of the accuracy of the remotely collected data and a baseline against which future changes in canopy cover and tree density can be measured. Canopy growth in future years was predicted using a growth model. Targets were specified to increase the canopy cover to the city average for each land use and each ward. The number of trees that would need to be planted in Cambridge per year over five years in order to attain these targets was calculated to be 3,000.

Introduction

The benefits of urban trees in the context of urban climate change adaptation are widely recognised (Konijnendijk *et al*., 2005). In order to achieve maximum benefit from our tree stock, resources must be allocated to effectively manage urban trees. Estimates suggest that the average lifespan of a typical urban tree is 32 years, and that many newly planted trees do not survive the first year after planting (Moll and Ebenreck, 1998). Species selection is also important, with aesthetic merits in direct competition with attributes such as drought tolerance and larger canopies. The most beneficial attributes of urban trees are rapid growth to a large size at maturity and a long lifespan (Armour *et al*., 2012).

Urban trees can provide benefits such as the reduction of air pollution, increased shade and cooling, increased carbon sequestration, reduced flood potential (via water interception and storage) and improved human health and wellbeing. It is important to plan tree planting strategies within cities as early as possible in order for their full potential to be realised by the time the negative impacts of climate change are predicted to reach a high in the 2080s (UKCP09 Climate Change Projections).

The Trees in Towns II project (Britt and Johnston, 2008) heightened policy understanding of the importance of urban trees and their contribution to mitigating climate-induced effects. The project revealed an unsatisfactory age structure in the national urban tree population, with a lack of young and large mature trees. Defra's 2007 Delivery Plan for England's trees proposed actions including the provision of more shade in cities. The Read (2009) report recommended that tree planting should occur where people live and gather, particularly where canopy cover is sparse. The Natural Environment White Paper (2011) identified the health benefits of trees, and the National Planning Policy Framework (2012) stated that green infrastructure (GI) is a key element

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of sustainable development and urban forest a key component of GI.

Cambridge City Council has been taking action to tackle climate change for over 15 years. The Council made a formal commitment to play a part in the international effort to address the causes and consequences of climate change by signing the Nottingham Declaration on Climate Change in September 2006. Its first five-year Climate Change Strategy and Action Plan was published in September 2008 (CCC, 2008), and set out a clear vision and framework for increased action relating to managing the risk posed by climate change. It covered flooding, water supply, heat, high wind speeds and subsidence. Urban trees can provide benefits against most, if not all, of these aspects. The Green Infrastructure Strategy for Cambridgeshire was published in 2011. Cambridge city is one of the target areas in the strategy, and the importance of taking opportunities to enhance the GI in development localities is stressed.

The aim of this project was to provide Cambridge City Council (CCC) with an evidence base that can be used to enhance the benefits that urban trees in Cambridge provide to help the city and its residents adapt to the detrimental effects of climate change.

This evidence base will be used to:

- inform wider Council policy with regards to influencing desired canopy cover targets
- add weight to any tree management policy that is developed for the city
- enable the Council to cost effectively target tree planting in areas of low canopy cover
- identify areas where currently unprotected trees with large canopies are located
- provide a baseline by which to measure future changes in tree stock quantity and quality
- set measureable targets for canopy cover in the city
- inform the Council of the health and fitness of its stock with respect to risks from climate change.

Methodology

Cambridge city was classified by land use, and a spatial analysis was carried out on its tree stock data, providing a breakdown of density and structure by ward, land use class, ownership, conservation area and Tree Preservation Order (TPO). A stratified sample of plots was surveyed to assess the accuracy of the data and to provide a baseline against which to assess change. Targets for canopy cover by ward and land use class were suggested and methods proposed to achieve this.

Land Use Classification

Tree density and canopy cover vary significantly by land use, therefore a simple method of land classification was required. Land use in Cambridge was classified based on the methodology in the Trees in Towns II report (Britt and Johnston, 2008). The land use classes were Town Centre and Commercial (TC), Low Density Residential (LDR), Medium Density Residential (MDR), High Density Residential (HDR), Industrial (I), Formal and Informal Open Space (OS1), Institutional Open Space (OS2), Derelict, Neglected and Abandoned Open Space (OS3) and Remnant Countryside (OS4).

Datasets

CCC used a digital tree map layer (ProximiTREE™) covering the entire city that details the spatial location, height and canopy area of individual trees as captured from aerial photography stereo images. This dataset formed the basis of most of the analyses in the study. The geographic boundaries of wards, CCC freehold land and highways land were made available. Land ownership was categorised into city council land, highways and privately owned based on these boundaries. Conservation Areas and TPO areas and trees were used to provide an assessment of canopy area that is statutorily protected but privately owned.

Analysis by Ward, Land Use Class and Ownership

The point locations of each tree in the ProximiTREE dataset were overlaid onto a polygon dataset covering the city in ArcGIS, with each polygon attributed with its ward, land use and land ownership. Each tree could thus be assigned a ward, land use and ownership class.

The total land area within each ward, land use and ownership class were calculated to enable the estimation of tree density (trees ha^{-1}) for each group.

The canopy cover area was derived by merging the individual canopies in order to remove the overlapping area between separate canopies. The canopy cover density (m^2 ha^{-1}) was then calculated for each ward, land use and ownership group by intersecting the land classification layer with the merged canopy dataset.

Data on tree height was further subdivided into height classes (0.0-2.4 m, 2.5-4.9 m, 5.0-9.9 m, 10.0-14.9 m, 15.0-19.9 m and 20.0+ m). The canopy spread of each tree was calculated from the area of each individual canopy by calculating the diameter of each circle representing individual canopies. The trees were then subdivided into canopy spread classes (0.0-1.9 m, 2.0-4.9 m, 5.0-9.9 m, 10.0-14.9 m, 15.0-19.9 m and 20.0+ m).

Analysis by Conservation Area and TPO

Canopy cover and tree density data were also analysed by private protection status. This included privately owned land in Conservation Areas, TPO areas and individual TPOs. In order to include only the parts of the Conservation Areas containing privately owned trees, the highways and council freehold land areas were removed from the Conservation Areas. The canopy cover (m^2) was then calculated for each type of protection status and summarised by ward. The canopy cover was also analysed for privately owned trees in each Conservation Area in Cambridge.

The number of trees found in conservation areas in each height and canopy spread group was analysed by ward and Conservation Area.

Ground Survey

A ground survey of trees within 24 200 x 200m (4 ha) plots selected to be representative of the land use classes within the city was performed. The objectives of the ground survey were to provide some validation of the ProximiTREE data in terms of tree density and canopy spread and height splits, to obtain robust estimates of the characteristics of the tree stock in the city (species, age, maturity and condition) and to provide a baseline against which future changes in the tree population could be assessed.

A stratified random approach to sample plot selection was taken to ensure that the sample was representative of the land use classes within the city. The stratification is shown in Table 1.

Table 1: Survey plot stratification by land use class

Land Use Class	Area of City (ha)	Proportion of Total Area	Survey Plots Required
Town Centre and Commercial (TC)	314	0.08	2
Industrial (I)	186	0.05	1
Low Density Residential (LDR)	160	0.04	1
Medium Density Residential (MDR)	1,281	0.31	8
High Density Residential (HDR)	173	0.04	1
Formal and Open Space (OS1)	263	0.06	1
Industrial Open Space (OS2)	657	0.16	4
Derelict, Neglected and Abandoned Open Space (OS3)	28	0.01	0
Remnant Countryside (OS4)	1,018	0.25	6
Total	**4,080**	**1.0**	**24**

Plots were randomly selected within the land use class in a GIS, whereby a 2 x 2 km grid was overlaid onto the land use class map and grid cells with at least 90% of their area within one land use class were identified for possible selection. Possible sample plots were numbered and then selected at random from within the land use class until the sample quota was met for that land use class.

All of the ground surveyors were experienced arboriculturists qualified to level 5 or above in the National Qualifications Framework. The data were recorded in Excel spreadsheets on hand-held computers for every clearly visible tree or group of trees within each selected plot. All visible shrubs greater than 2.5 m tall were also recorded. Surveyors were not expected to seek access to back gardens or other small plots of private land, although every reasonable effort to view the trees was expected. Permission for access to industrial sites, hospitals, utility owned land or other larger plots of private land was sought in every case.

The survey information collected included the following.

- Location – the GPS Easting/Northing.
- Groups – if trees formed a group, defined as '*two or more trees that clearly form a single entity of mutual benefit*', an estimate of the number of trees and species in that group.
- Tree number – the unique number for each tree or group of trees.
- Ownership – the apparent 'status' or ownership of the land upon which each tree or group was located, recorded as one of:
  Public: trees on the roadside verge, pavement, central reservation, parks or open space that could be clearly seen and readily accessed
  Private: trees in gardens, churchyards, schools, allotments and private parking areas
  Unknown: trees on land where the ownership was not clear.
- Species/variety/cultivar.
- Stem diameter – measured at 1.5 m above ground level using a diameter tape. If the tree was not located on level ground, the diameter was measured from the upper side of the tree.
- Height – estimated visually from the ground to the top-most shoot tip.
- Crown spread – the maximum diameter of the crown spread as estimated visually, regardless of orientation.
- Age – estimated in years.
- Tree maturity – estimated as:
  Young – planted within the last three years
  Semi-mature – planted at least three years ago and yet to attain mature stature; up to 25% of attainable age
  Early mature – almost full height, crown still developing and seed bearing; up to 50% of attainable age
  Mature – full crown size, seed bearing; over 50% of attainable age;
  Late mature – full crown size, developing early signs of decline such as initial dieback in the branch extremities and reduced vigour observed in the annual shoot extension in relation to that of a healthy tree of the same species
  Over mature – reduced overall crown size, advanced dieback of branches, small leaf size and poor shoot extension in relation to that of a healthy tree of the same species.
- Condition – allocated as one of four tree condition categories, taking into account, health, vigour, local environment, vandalism and pathogenic attack:
  Good – no evidence of disease or damage; full leaf, no canopy or branch die-back, balanced branch structure
  Fair – evidence of pests, diseases or other factors with the potential to impact on tree health and vigour observed, but not considered to be life threatening to the tree either due to the nature of the pest or disease or as a result of the overall health of the tree
  Poor – trees in such a condition that their long-term safe and healthy retention was not viable. Indicators visible in the tree included, but were not limited to, leaf discolouration, reduced foliar density, significant amounts of deadwood, dieback, reduced annual growth increments
  Dead/dying – trees where the indicators stated for Poor trees had become so advanced as to make the survival of the tree the next five years unlikely, or dead trees.

Canopy Growth Modelling

A growth model was used to calculate the canopy cover that would be achieved under a number of tree planting scenarios. The aim was to aid the prediction of the number of trees that would need to be planted across the city of Cambridge to achieve any specified canopy increases.

Modelling was performed to predict canopy growth over 30 years for one tree planted each year over five years. The figures were based on a newly planted tree with a canopy of 0.5 m radius with no growth in year 1 or 2 due to establishment stresses. Subsequent shoot extension growth was estimated to increase by 0.155 m annually (Bradshaw *et al*., 1995), resulting in trees planted in year 1 having an average canopy radius of 5.02 m and an area of 79.17 m^2 after 30 years of growth. This model is shown in Table 2.

Table 2: Canopy area prediction

Year	Canopy Area (m^2)
1	0.79
2	1.57
3	2.92
4	4.98
5	7.91
10	37.55
15	83.99
30	336.53
25% Loss	252.40

The model was also used to estimate the resultant percentage increase in canopy cover in the city that would be obtained under each of four scenarios.

Scenario 1 – planting targeted within each ward to achieve the city average canopy density by land use and ownership class.

Scenario 2 – planting targeted within each ward to achieve the city average canopy density by land use class.

Scenario 3 – planting targeted within each ward to achieve the city average canopy density by ownership class.

Scenario 4 – planting targeted within each ward to achieve the city average canopy density.

This model was also used to estimate the number of trees that would need to be planted each year over five years to attain canopy cover targets under the most appropriate scenario.

Results

City Land Use

A map of the distribution of land use classes within Cambridge city is shown in Figure 1.

Tree Stock by Ward

The mean number of trees per hectare across the city was estimated at 33.2. This varied from 17.2 trees ha^{-1} in Market ward to 52.1 trees ha^{-1} in West Chesterton ward (Table 3). The mean canopy cover in the city was 1,700m^2 ha^{-1}, ranging from 1,278 m^2 ha^{-1} in Cherry Hinton ward to 2,265 m^2 ha^{-1} in Newnham ward. Generally, tree stock and canopy cover in each ward were proportional to the land area that the ward occupied. Notable exceptions were Abbey ward, where canopy cover was sparser than expected in relation to its land area; East Chesterton, where the number of trees was higher than expected; Newnham, which had a higher canopy cover than expected

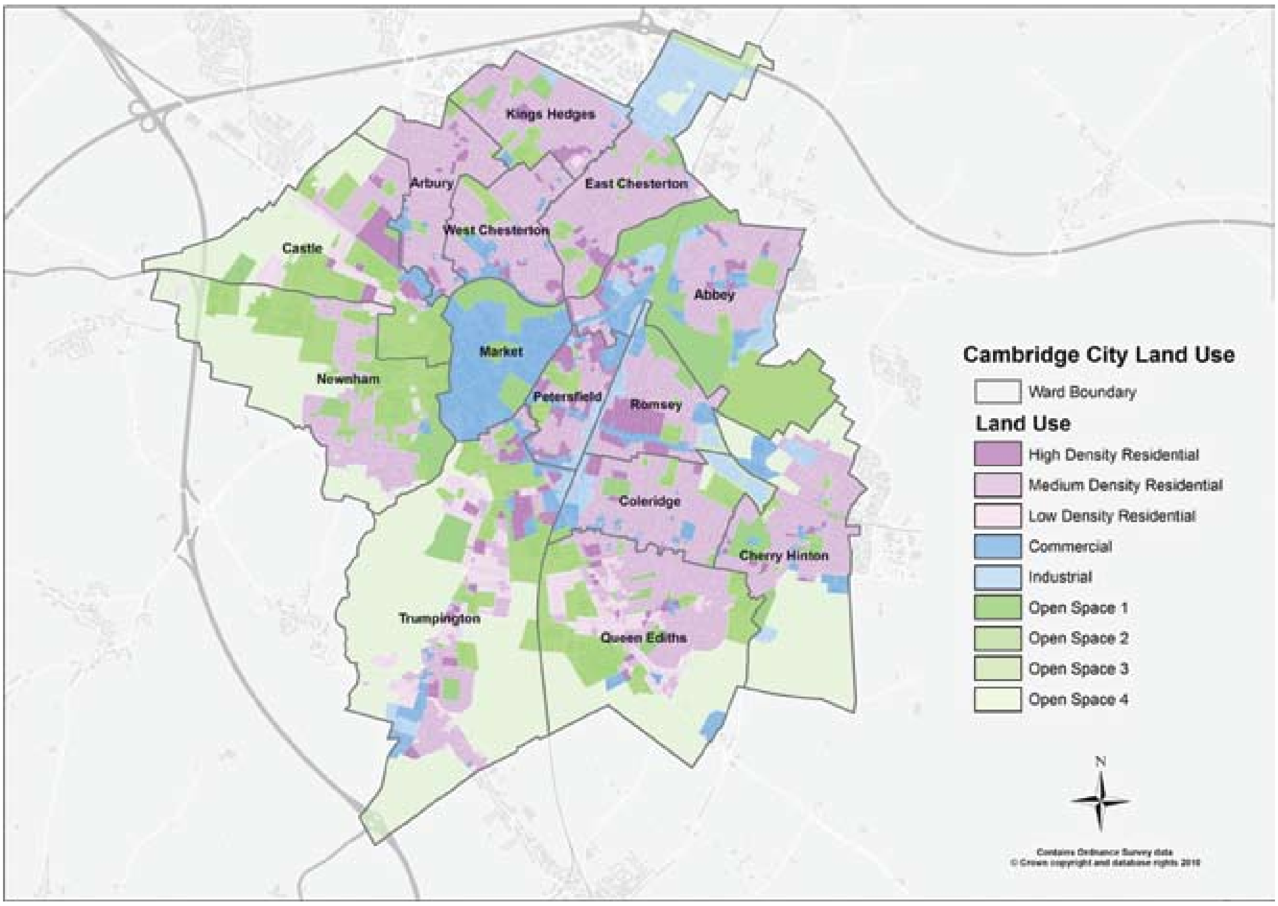

Figure 1: Distribution of land use classes within Cambridge city

Table 3: Tree statistics in Cambridge by ward

Ward	Number of Trees (%)	Canopy Cover (%)	Land Area (%)	Tree Density (Trees ha^{-1})	Canopy Density (m^2 ha^{-1})	Average Canopy Size (m^2)
Abbey	9.1	7.3	9.7	31.3	1,290	41.2
Arbury	4.6	3.7	3.7	41.3	1,718	41.6
Castle	7.8	10.1	8.4	31.1	2,068	66.5
Cherry Hinton	9.8	6.8	9.0	35.9	1,278	35.6
Coleridge	5.1	4.0	4.8	35.5	1,440	40.6
East Chesterton	9.3	6.3	6.4	48.3	1,664	34.5
King's Hedges	4.9	3.8	3.9	41.8	1,651	39.5
Market	2.2	3.6	4.2	17.2	1,477	85.9
Newnham	10.0	14.4	10.9	30.6	2,265	74.0
Petersfield	2.8	2.5	2.6	35.9	1,649	45.9
Queen Edith's	12.1	11.6	11.1	36.3	1,793	49.4
Romsey	4.2	3.2	3.6	38.6	1,479	38.3
Trumpington	12.2	18.8	18.0	22.5	1,783	79.2
West Chesterton	5.9	3.9	3.8	52.1	1,767	33.9

and Trumpington, which had a lower number of trees than expected. The average canopy size was approximated by dividing the canopy density by the tree density (Table 3). The largest trees were found in Market, Newnham and Trumpington wards.

Tree Stock by Land Use

Tree density ranged from 13 trees ha^{-1} in Remnant Countryside (OS4) to 61 trees ha^{-1} in Derelict, Neglected and Abandoned Open Space (OS3, which only covered 1% of the land area). Densities of over 50 trees ha^{-1} were found in the Low Density Residential (LDR) and Medium Density Residential (MDR) areas. Canopy density ranged from 752 m^2 ha^{-1} in Industrial areas to 4,171 m^2 ha^{-1} in LDR. Land use varied markedly between wards, which was probably the main reason for the variation in tree and canopy densities between wards.

In terms of tree numbers, over half of the trees in Cambridge fell into the MDR land use class (Table 4). This is to be expected, considering that it is the most common land use type in Cambridge; however, the tree density was still disproportionately higher than the proportion of the land area covered by this class. The proportion of the canopy cover in MDR (37%) areas was more similar to the proportion of land area occupied by MDR land (31%).

The Town Centre and Commercial (TC) and, in particular, Industrial (I) land use classes had a disproportionately small number of trees and canopy cover compared with the size of the areas they occupied.

The Institutional Open Space class (OS2) covered a relatively large proportion of the Cambridge area and had the second greatest proportion of trees and canopy cover after the MDR class. This land use class includes the university colleges and their grounds, which typically contain mature trees with large canopy areas.

Despite 25% of the Cambridge area being classified as OS4, it contained *c.* 10% of all trees and 14% of the canopy cover, possibly because this land use class consists largely of open arable fields that often only have trees and shrubs at their boundaries.

The average canopy size calculations (Table 4) suggested that the MDR and industrial areas had trees with the smallest canopies.

Maps by each unique ward/land use classification of tree and canopy density are shown in Figure 2 and Figure 3, respectively. These demonstrate that, whilst the highest tree densities were scattered throughout the city, they were particularly concentrated in the northern and eastern parts. More specifically,

Table 4: Proportion of total number of trees, canopy cover and land area in Cambridge by land use class

Land Use Class	Number of Trees (%)	Canopy Cover (%)	Land Area (%)	Tree Density (Trees ha^{-1})	Canopy Density (m^2 ha^{-1})	Average Canopy Size (m^2)
LDR	6.9	9.6	3.9	58.7	4,171	71.1
MDR	53.3	37.6	31.4	55.7	2,015	36.2
HDR	4.3	3.9	4.2	33.7	1,728	51.3
TC	5.3	5.9	7.7	22.9	1,311	57.2
I	2.6	2.0	4.5	19	752	39.6
OS1	5.0	8.1	6.4	26	2,147	82.6
OS2	11.5	17.3	16.1	23.8	1,836	77.1
OS3	1.2	1.6	0.7	61.2	4,066	66.4
OS4	9.8	13.9	25.0	13.1	954	72.8

East and West Chesterton had the highest tree densities and Market and Trumpington the lowest. Conversely, canopy densities were markedly highest in the southern and western areas, with Newnham and Castle characterised by the highest canopy densities and Cherry Hinton and Abbey by the lowest. Comparing average canopy size between wards helps explain the low tree density in Market and Trumpington, since it appears that these wards contained the largest trees (Table 3).

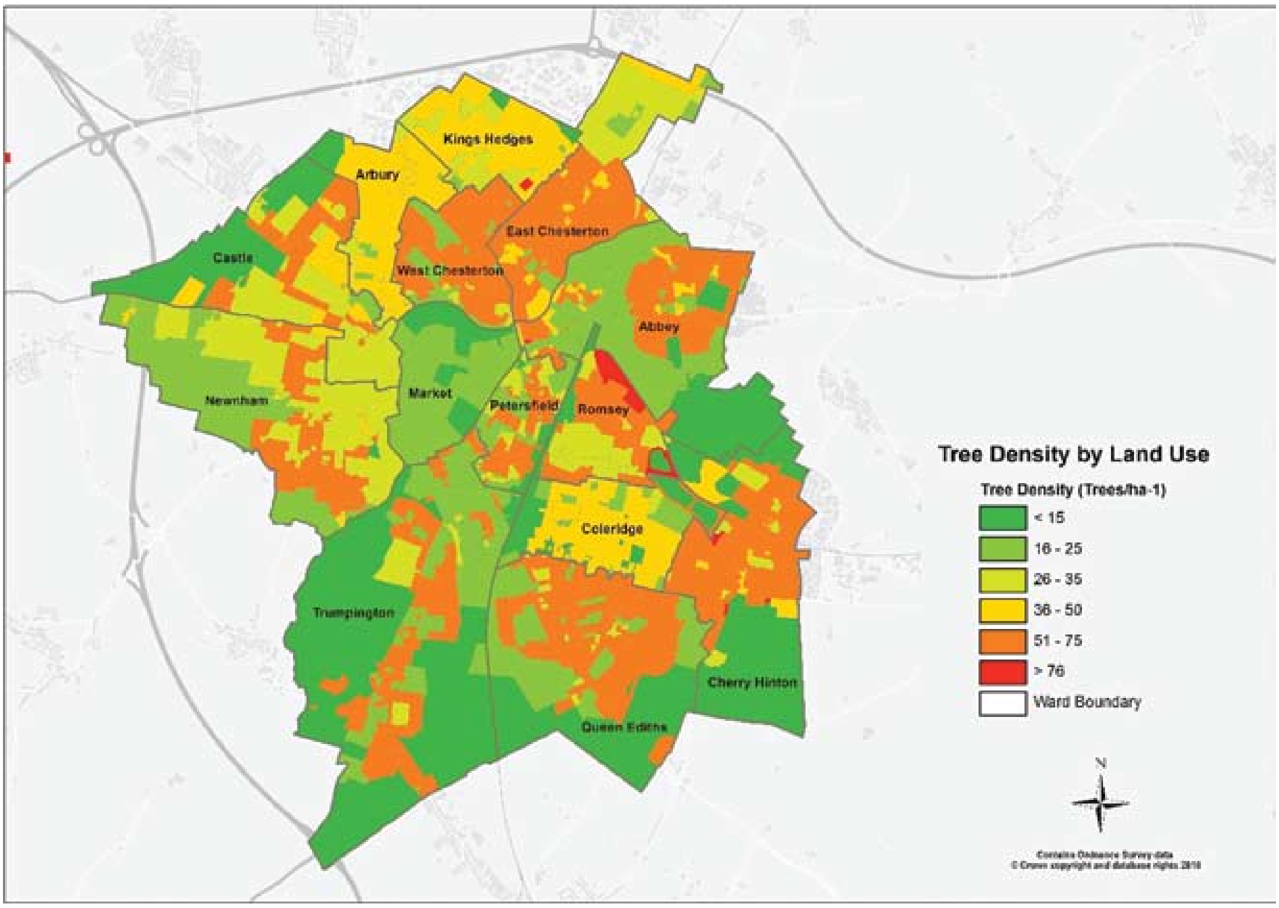

Figure 2: Tree density by ward and land use in Cambridge city

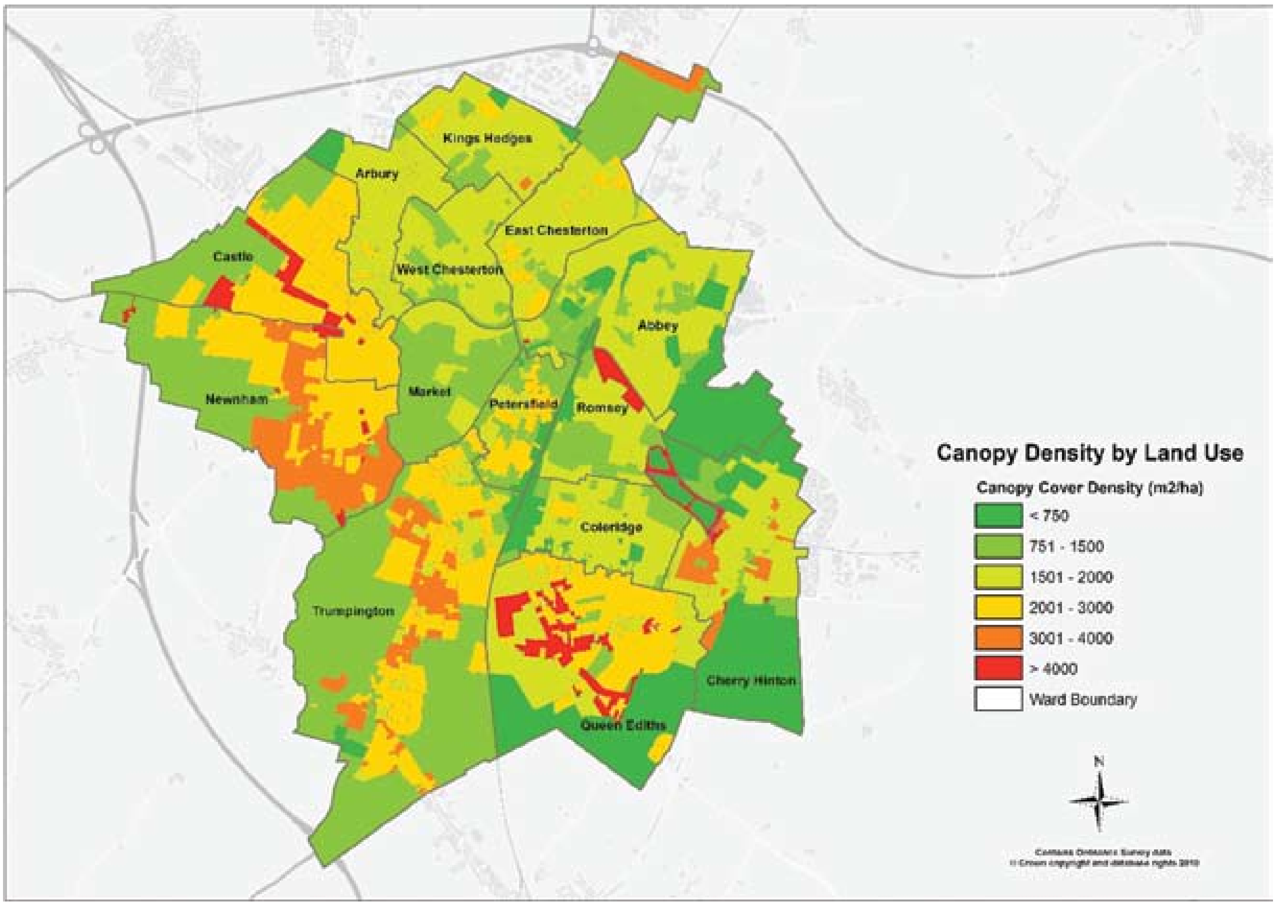

Figure 3: Canopy density by ward and land use in Cambridge city

Tree Stock by Ownership

The majority (77%) of the land area in Cambridge was privately owned. City council land comprised 13.5%, with highways comprising the remainder. Tree numbers and canopy cover were found to be similar proportions, both at a city and ward level (Table 5). Exceptions included Abbey and Cherry Hinton wards, where canopy cover in the city council and highways categories was higher than expected based on land area.

Table 5: Proportion of the total number of trees, canopy cover and land area in Cambridge by ownership

Ownership	Number of Trees (%)	Canopy Cover (%)	Land Area (%)
City council	14.6	16.3	13.5
Highway	9.3	9.6	9.5
Private/other	76.1	74.1	77.0

Land ownership was not equally distributed between wards (Figure 4). More privately owned land was located in the southern and western wards, with more city council owned land in the northern and eastern wards. Highways land was more evenly distributed amongst the wards.

Canopy cover area by ownership showed a similar distribution at ward level to the land area by ownership (Figure 5). Some wards in the north and east of the city had a higher proportion of canopy cover in the city council and highways categories than land area in these categories, most notably Abbey and Cherry Hinton.

Height and Canopy Spread

Almost 75% of the trees in Cambridge were between 2.5 and 10 m high. Less than 2% were over 20 m tall (Table 6). The OS2 land use class had the greatest proportion of trees over 15 m tall, which most likely reflects the abundance of large mature specimens on university-owned land. Over 75% of the trees had a canopy spread of between 2 and 10 m (Table 7). Less than 2% had a canopy spread of less than 2 m or over 20 m. The open space categories had the greatest

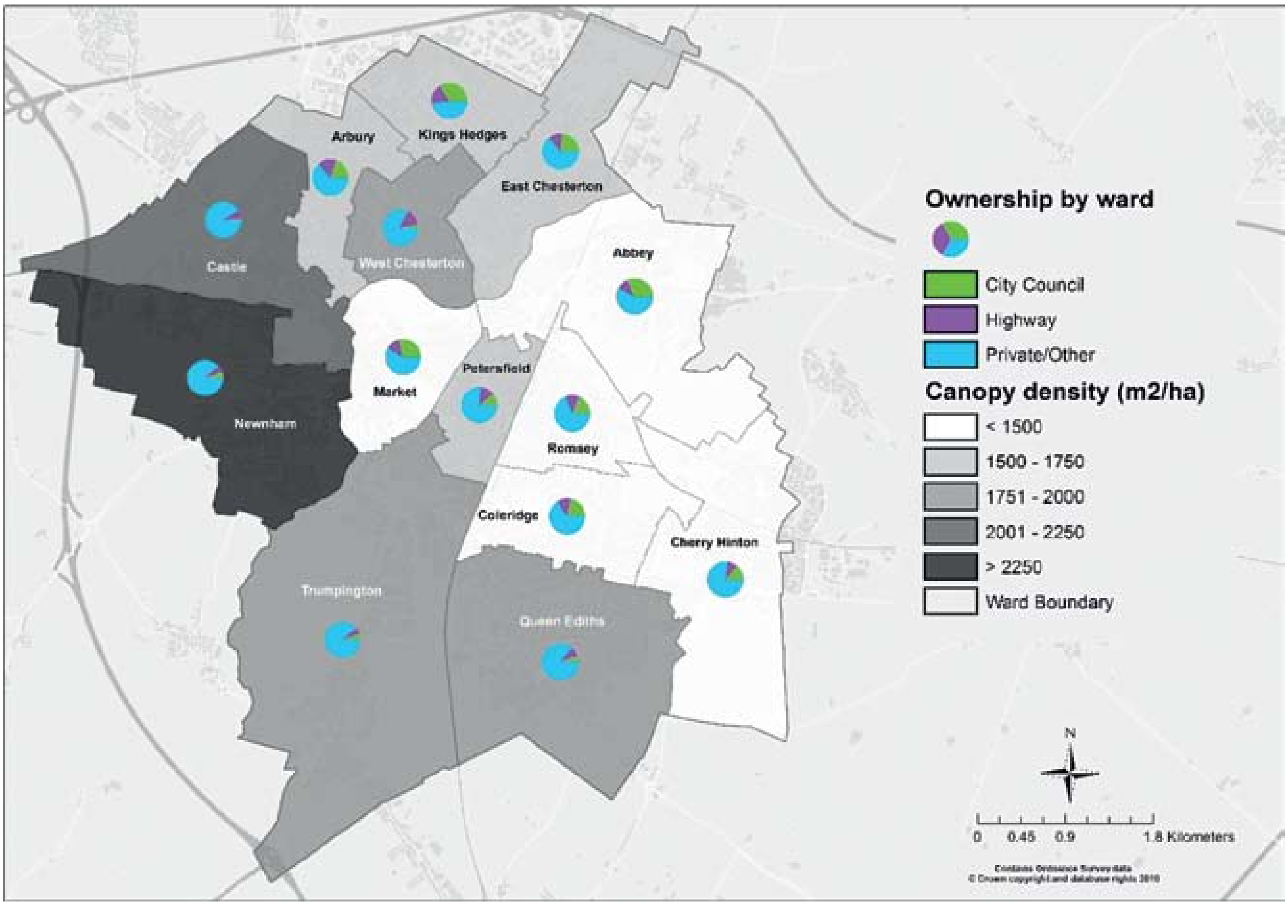

Figure 4: Land ownership by ward overlaid onto a map of canopy density at ward level

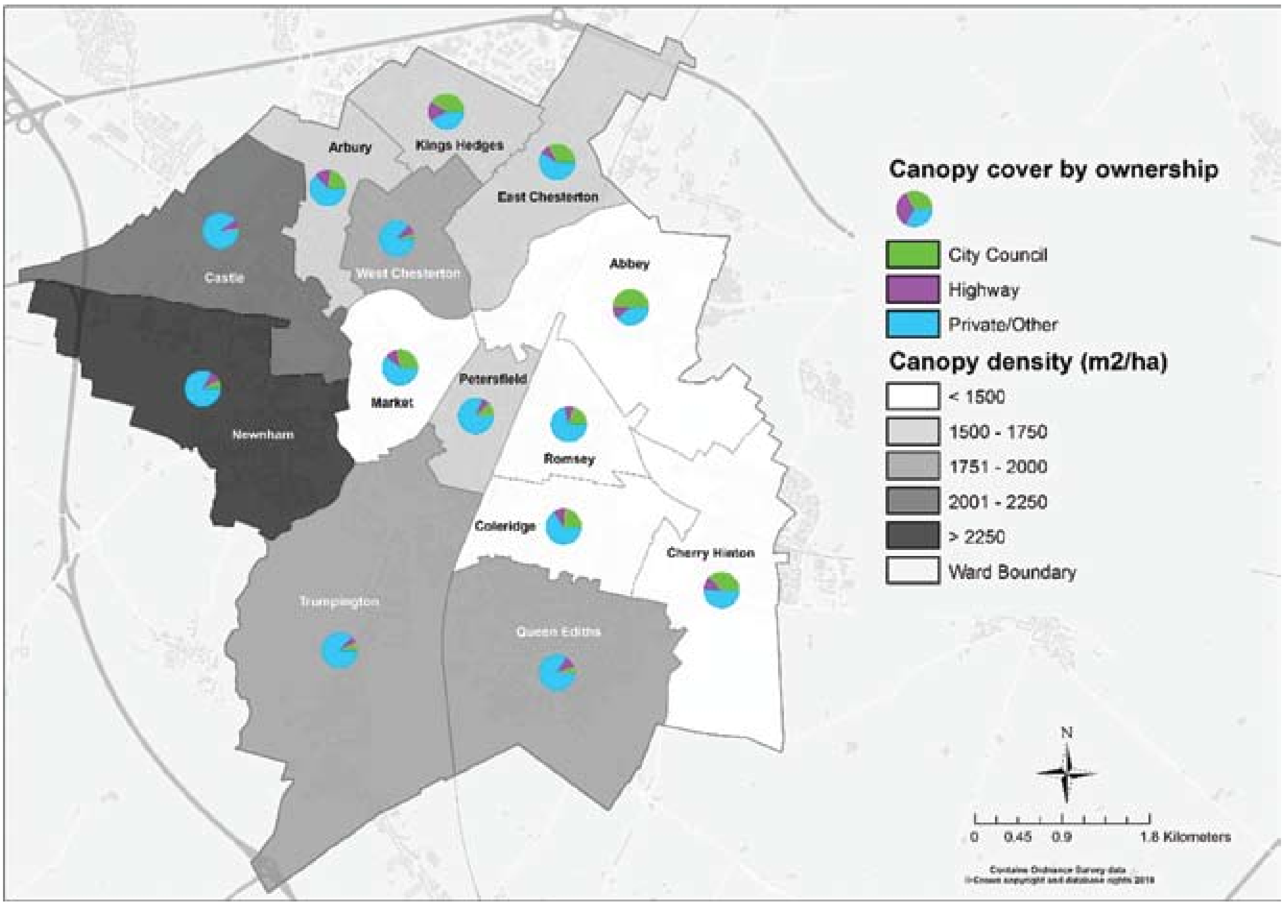

Figure 5: Canopy cover by ownership by ward overlaid onto a map of canopy density at ward level

Table 6: Proportion of trees in each height class by land use class in Cambridge

Land Use Class	Tree Height Group					
	0.0-2.4 m	2.5-4.9 m	5.0-9.9 m	10.0-14.9 m	15.0-19.9 m	20+ m
LDR	3.3	21.9	43.7	19.6	9.1	2.4
MDR	7.2	41.9	39.4	8.9	2.1	0.5
HDR	4.7	30.1	45.0	13.8	5.2	1.2
TC	6.0	29.1	36.7	17.4	8.4	2.4
I	4.0	35.3	45.8	13.5	1.4	0.1
OS1	2.5	18.2	45.2	21.0	9.4	3.8
OS2	3.2	21.1	37.5	19.9	12.6	5.7
OS3	2.7	28.8	53.7	12.9	1.5	0.4
OS4	5.6	37.6	31.7	15.5	7.1	2.5
Total	**5.8**	**35.0**	**39.4**	**13.0**	**5.1**	**1.7**

NB. The rows add up to 100%.

Table 7: Proportion of trees in each canopy spread group by land use class in Cambridge

Land Use Class	Canopy Spread Group					
	0.0-1.9 m	2.0-4.9 m	5.0-9.9 m	10.0-14.9 m	15.0-19.9 m	20+ m
LDR	0.1	14.7	48.5	26.4	8.4	1.8
MDR	2.1	38.7	47.2	9.9	1.8	0.3
HDR	0.7	30.8	50.6	14.0	3.2	0.8
TC	1.7	29.7	42.2	19.4	5.5	1.4
I	0.8	36.1	47.5	13.0	2.4	0.3
OS1	0.3	16.1	41.7	26.8	11.8	3.3
OS2	0.6	20.0	39.5	26.0	10.8	3.0
OS3	0.2	11.0	52.2	27.6	7.7	1.2
OS4	0.4	22.5	41.3	19.8	10.6	5.5
Total	**1.4**	**30.9**	**45.5**	**15.7**	**5.0**	**1.4**

NB. The rows add up to 100%.

abundance of trees with canopies over 15 m. The MDR class had the greatest proportion of trees with canopies under 5 m. Castle, Newnham, Market and Trumpington wards had the highest proportions of taller trees.

Protected Stock

Overall, 25% of the canopy cover in the city was in private ownership in Conservation Areas (Table 8). There was great variation between wards, with four wards having no conservation areas. On average across the city, 4% of canopy cover was within TPO areas and 9% was associated with trees with individual TPOs. There were a number of wards in which the majority of the canopy cover had protected status. Within the Conservation Areas, 75% of the trees were over 5 m high, compared with *c.* 60% in the city as a whole. In terms of city trees over 20 m high, 56% were on privately owned land in Conservation Areas. Of the city trees with a canopy spread over 20 m, 31% were on privately owned land in Conservation Areas.

Table 8: Percentage of total canopy cover by ward within protected areas (Conservation Areas and TPO areas) and of trees with individual TPO status

Ward	% of Canopy Cover in Conservation Areas (Privately Owned)	% of Canopy Cover in TPO Areas	% of Canopy Cover with Individual TPOs
Abbey	2.2	0.3	5.4
Arbury	2.6	2.1	3.6
Castle	50.3	3.2	10.4
Cherry Hinton	0.0	1.9	3.1
Coleridge	0.0	0.9	2.1
East Chesterton	6.5	3.8	5.7
King's Hedges	0.0	1.8	2.4
Market	60.5	0.2	7.0
Newnham	52.5	3.1	11.4
Petersfield	70.0	4.6	30.4
Queen Edith's	0.0	9.8	21.2
Romsey	19.8	0.5	11.1
Trumpington	37.1	9.6	6.7
West Chesterton	13.9	0.3	6.2
Total Area	**25.4**	**4.4**	**9.3**

Ground Survey

A total of 4,639 trees were surveyed within an area of 74.2 ha, resulting in a density estimate across the city of 58.5 3 8.3 ha. The highest tree densities were found in the Industrial, OS2 and OS4 land use classes. The counts for the same land areas from the ProximiTREE data were within 5% of the survey counts for the Industrial, MDR and HDR land use classes and were slightly less accurate but moderately similar for the LDR class. In the TC class, the ProximiTREE estimates were twice as high as the ground survey counts, possibly due to the classification of shrubs as trees. In the OS classes there were three to four times more trees counted during the ground surveys than were estimated in the ProximiTREE dataset. This appeared to be due to the underestimation of tree numbers in very densely wooded areas by the ProximiTREE method.

The surveyed trees tended to be taller than those in the ProximiTREE dataset, particularly in the middle height classes. This may be due to the four years worth of growth between the date of the aerial photography and the time when the ground survey was performed. The surveyed trees tended to have smaller canopies than the ProximiTREE trees, which may be an artefact of the fewer trees estimated in the OS categories covering a similar area in terms of canopy.

The most common tree family surveyed was Rosaceae (28%), followed by Oleaceae (21%). The most common genus was *Fraxinus* (>20%) followed by *Prunus* (>15%). Of the surveyed trees, 71% were found to be in good condition and only 2% in poor condition or dead. The majority (38%) of surveyed trees had a stem diameter of 10-20 cm. Forty per cent of the surveyed trees were estimated to be 5-10 years old and 32% between 25 and 50 years old. Forty per cent were classed as semi-mature and 32% as young.

Canopy Cover Modelling

Table 2 predicts an increase in canopy cover for one tree planted every year over five years, resulting in a canopy cover of 252.40 m^2 in 30 years' time. This estimate takes into account tree loss of 25% due to stress and other factors such as pest and disease attacks.

Using the figures formulated in the growth model, the differences in canopy cover for each ward in the relevant land use or ownership class as well as the city average for that class, the overall canopy increase and number of trees that would need to be planted to achieve this, were determined.

The predicted canopy increases under each scenario were as follows.

- Scenario 1 – targets by ward, land use and ownership gave a percentage increase in canopy area of 2.26%.
- Scenario 2 – targets by ward and land use gave a percentage increase in canopy area of 2.01%.
- Scenario 3 – targets by ward and ownership gave a percentage increase in canopy area of 1.66%.
- Scenario 4 – targets by ward only gave a percentage increase in canopy area of 1.16%.

It was concluded that Scenario 2 was the most achievable. The omission of the ownership factor allowed tree planting requirements in each ward to be increased by the city council when there were limiting factors within the private and highways owned land for a specific land use type.

Tables 9 and 10 summarise the tree planting requirements by ward for Scenario 2.

Table 9: Scenario 2 tree planting requirements and resultant canopy cover increase by ward

Ward	Total Trees Planted	Trees Planted Per Year over 5 Years	Canopy Cover Increase (m^2)
Abbey	4,174	835	210,710
Arbury	600	120	30,273
Castle	447	89	22,584
Cherry Hinton	2,432	486	122,779
Coleridge	1,625	325	82,019
East Chesterton	1,111	222	56,078
Kings Hedges	1,096	219	55,350
Market	402	80	20,295
Newnham	11	2	549
Petersfield	123	25	6217
Queen Ediths	2,481	496	125,247
Romsey	868	174	43,810
Trumpington	356	71	17,973
West Chesterton	484	97	24,426
Total	**16,210**	**3,242**	**818,307**

Table 10: Scenario 2 – Current and projected canopy characteristics

Current Canopy Cover (m^2)	6,961,907
Future Canopy Cover (m^2)	7,780,214
Per Cent Increase in Canopy Cover	11.75
Current Canopy Cover as Per Cent of Land Area	17.08
Future Canopy Cover as Per Cent of Land Area	19.08
Actual Percentage Increase in Canopy Cover	2.01

Discussion

Implications of the Results for Climate Change Adaptation in Cambridge

The vast majority of trees in Cambridge are privately owned, which has implications for the design of local policies for tree planting. The focus will need to be on partnerships with institutions such as the university, as well as guidance and schemes advising local residents on how they can increase canopy cover.

Industrial land had one of the lowest tree densities in Cambridge. There may be scope for increasing tree density in this land use class by encouraging boundary planting. For example, highways land could be targeted to reduce the effects of traffic pollution. Planting on more centrally located industrial land would be beneficial in reducing the urban heat island effect and modifying airflow.

Council-owned OS1 land, particularly in the central wards, could also be targeted for tree planting. This land use category includes amenity areas and parks. Planting in these areas would greatly increase the health benefits to members of the public.

Canopy cover plays an important part in providing the majority of benefits for climate change adaptation in an urban setting, particularly reducing the heat island effect, intercepting precipitation and removing urban pollutants. Maximising the canopy cover provided by a specified number of trees is therefore a useful strategy if the land use type can support larger trees. The selection of appropriate species should be encouraged, both by the city council, county council and homeowners. Tree species diversity should be encouraged to lessen the potential impact of an increased pest and disease risk due to climate change. If variation in species is low, then the potential impact on tree populations is greater.

In terms of protecting the tree stock, a more targeted approach than that which has been applied to date could be considered, such as assessing those trees with greater potential to offset the effects of climate change. Larger trees or species that will be large at maturity should be prioritised for protection.

Recommendations from the Ground Survey Results

A comparison of the ground survey results with the ProximiTREE data concluded that the ProximiTREE estimates of tree densities were relatively robust apart from where dense woodland was present. Whilst the canopy densities could not be obtained from the ground survey data, the canopy spread tended to be lower for the ground surveyed trees than for the ProximiTREE trees in areas where the tree densities were higher than the ProximiTREE estimates. This indicates that the canopy densities were more accurate than the tree densities from the ProximiTREE data in these areas. It is therefore recommended that canopy densities are used as the main metric for setting tree planting targets, rather than tree densities, to minimise potential spurious effects from underestimating tree densities in specific areas.

The results of the ground survey provide a baseline against which future changes in the city stock and its characteristics can be assessed. It is recommended that accessible surveyed areas are re-surveyed every one to two years to monitor the effects of the implementation of local policy to improve the quality and quantity of the tree stock.

Conclusions for Policy Inception

Canopy growth over future years was predicted for four scenarios using a growth model. The results of this process were used to calculate the number of trees that would need to be planted each year over five years in order to attain the canopy cover targets for each scenario. Achieving the targets for the recommended scenario (Scenario 2, targets set by land use and ward) would result in a 2% increase in canopy cover (from 17.1% to 19.1%) across the city's land area within 30 years. The level of planting that would be required to achieve this increase was estimated at over 3,000 trees per year over a five-year period.

Research by Gill *et al*. (2007) identified that increasing the canopy cover by 10% in locations with limited vegetation could decrease urban temperatures by up to 2.5°C based on urban temperature predictions up to 2080. This research relates specifically to urban areas with limited canopy cover, yet as Cambridge city comprises numerous non-urban land use classes, targets should be set accordingly to take this factor into account. A 2% increase could be achieved by increasing canopy cover across wards and land use classes to meet the city average. An aspirational increase of 5% should be considered as a secondary target for the city. Similar targets have been proposed by the Forestry Commission: "In principle, the Forestry Commission's minimum policy objective is that development ought, through Green Infrastructure provision, to lead to an increase in tree canopy cover by 5%" (Forestry Commission, 2010). To achieve this secondary target, over 8,000 trees would need to be planted each year over a five-year period.

These targets could be achieved through a combination of initiatives that fall under four broad categories and address all aspects of tree management.

- **Strategic management** focused at policy level to harmonise arboricultural activities and goals specifically related to climate change, mainly by embedding tree management within wider policy targets.
- **New planting** to increase canopy cover by establishing partnerships and engaging with the community to promote the wider benefits of urban trees, and encouraging and incentivising tree planting.
- **Protection** of the existing tree stock and canopy cover through policy and best practice in design and service provision.
- **Maintenance** of the tree stock through correct management and increased replacement of failed tree stock where tree removal is necessary.

The increase in existing canopy cover can be optimised and tree mortality reduced by adopting, enforcing and promoting current best practice, codes of practice and statutory controls in the care, maintenance and protection of trees, in addition to the design and creation of tree-friendly places (Trees and Design Action Group, 2012).

Each strategy, or a number of methods to achieve strategic goals within different elements, should be targeted towards specific audiences within the population of Cambridge city. Examples of specific target audiences include large landowners, the Cambridge city electorate, highways, tree industry professionals and Cambridge City Council.

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