CENTRE OF EXPERTISE FOR WATERS

Quantifying rates of urban creep in Scotland: results for Edinburgh between 1990, 2005 and 2015

Photo credit: Kirsten Thorburn, SEPA

Photo credit: CEH, Copernicus Urban Data Atlas

Photo credit: Kirsten Thorburn, SEPA

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Research Summary

Understanding flood risk is important. One important factor affecting surface water flood risk is conversion of gardens, and other vegetated areas (which help soak up rain), to built-up surfaces (which are impervious), for example by building conservatories in back gardens, or paving over front gardens for car parking spaces. This process is called urban creep and the amount, and rates of, urban creep in urban areas of Scotland are poorly known. This project developed a method to map urban creep and applied it to aerial photography for Edinburgh for 1990, 2005 and 2015. This allowed the first city-wide estimates of urban creep to be produced for Scotland. The project also quantified urban expansion, which is the conversion of new land to urban areas, for example by building housing estates on farmland. The effectiveness of land use planning policy to ensure new development does not increase flood risk is important.

Research questions

Two objectives underlie this work:

1. To answer the question, what are the typical rates of urban creep for selected urban areas in Scotland?
2. To develop and test a transferable methodology for quantifying rates of urban creep in Scotland.

Main Findings

The main findings from this study are:

- Between 1990 and 2015 Edinburgh lost an average 11.27ha/year of vegetated land to urban land cover (from all types of change including urban creep and urban expansion). This is equivalent to losing over fifteen football pitches of vegetated land per year.
- The average annual rate of urban creep in Edinburgh (around buildings and their gardens and grounds), between 1990 and 2015, is 6.44ha/year. This is equivalent to losing over eight football pitches of vegetated land per year.
- The average annual rate of urban expansion in Edinburgh between 1990 and 2015 is 4.81ha/ year. This is equivalent to losing more than six football pitches of vegetated land per year.
- The highest rates of vegetation loss due to urban creep are for detached houses, which contribute on average 1.7ha/year of urban creep across Edinburgh. Semi-detached houses and bungalows also contribute high rates of urban creep of > 1ha/year.
- Flats and terraced houses have lower rates of urban creep with tall flats contributing the lowest rates of urban creep (<0.004ha/year) across Edinburgh.
- The maps of change show that urban creep is focused towards established peri-urban areas of the city and exhibits very low rates in the city centre. Urban expansion is clustered and located more towards the edges of the city.
- Where age of buildings is known, houses built between 1914 and 1945 contribute the highest rates of urban creep, at 1.51ha/year, across Edinburgh.

Background

Knowing more about factors that will influence future flood risk is essential to manage flood risk sustainably now and in the future, by:

- identifying where significant flood risks may arise in the future
- identifying if actions can be taken now to mitigate future changes
- making sure any actions implemented now are adaptable to future change
- Identify how future risks from flooding could change due to different investment scenarios and estimate the level of investment that would maximise benefits under different circumstances

Many factors influence flood hazard and flood risk and these can change over different timescales, the main factors are climate change, population and land cover change. The impacts of this are:

- by 2080 57,000 additional homes could be at risk due to climate change (from all sources of flooding; 13,800 additional homes specifically from surface water flooding). (based on data in the 2015 Flood Risk Management Strategies)
- by 2037 it is projected that 350,000 new homes may be built (from 2015 to 2037), the effectiveness of land use planning policy in avoiding flood risk to these new homes is important. (based on data from National Records of Scotland)

The loss of pervious surface in urban areas increases the risk of surface water flooding but the scale of this increase, and its impact on flood risk, is unknown.

This report details the methods and results of a CREW funded project to provide SEPA with potential methods for mapping urban creep (rate of urban creep and where it occurs) and some estimates of rates of creep for Edinburgh. The methods utilise high resolution aerial photography to map changes in impervious cover at the building plot scale – differentiating between new urban growth and urban creep. Upscaling of this mapping could provide more robust estimates of urban creep for Scotland. This report also provides some analysis of where urban creep occurred in Edinburgh, with some more spatially explicit breakdowns of observed rates according to housing type and age.

These results are important as:

- Further work could identify how best to include projections of future urban creep and extent of pervious ground into SEPA's pluvial flood hazard and risk modelling and mapping to determine the impact of urban creep on future surface water flood hazard and risk.
- Knowledge of future surface water flooding will be improved by considering climate change and urban creep scenarios.
- Better knowledge of areas at risk and the factors influencing surface water flood risk, both now and in the future, will enable improved management and mitigation.

1 Introduction

Understanding the role of urbanisation on flood risk is important. For planning new developments to mitigate the effects of impervious surfaces on localised and downstream flooding. The urban environment however is not stationary and is constantly evolving, requiring additional consideration of future changes that need to be considered in the planning phase. One particularly important factor affecting evolving flood risk is conversion of pervious surfaces such as gardens, and other vegetated areas, to built-up surfaces, for example by building conservatories in back gardens, or paving over front gardens for car parking spaces. This process is called urban creep and the amount and rates of urban creep in urban areas of Scotland are poorly known. This project developed a method to map urban creep and applied it to aerial photography for Edinburgh for 1990, 2005 and 2015. This allowed the first city-wide estimates of urban creep to be produced for Scotland. The project also quantified urban expansion, which is the conversion of new land to urban areas, for example by building housing estates on farmland. The effectiveness of land use planning policy to ensure new development does not increase flood risk is important.

1.1 Background

The Flood Risk Management (Scotland) Act 2009 has driven significant improvement in the understanding of flood risk (including surface water flood risk) and management of surface water flooding in Scotland. Consequently, the National Flood Risk Assessment in 2011 (NFRA 1) provided the first national maps of surface water flood hazard and risk were available for Scotland. In 2015, the first Flood Risk Management Strategies (FRM Strategies) set out a clear framework for the management of surface water flood risk; they require local authorities to lead on the development and implementation of surface water management plans in those areas with the greatest risk of surface water flooding. The 2015 FRM Strategies identified 113 towns and cities that require a surface water management plan, with surface water flooding accounting for 23% of annual flood damage in Scotland (by value).

Knowing more about factors that will influence future flood risk is essential to manage flood risk sustainably now and in the future, by:

- identifying where significant flood risks may arise in the future
- identifying if actions can be taken now to mitigate future changes
- making sure any actions implemented now are adaptable to future change
- Identify how future risks from flooding could change due to different investment scenarios and estimate the level of investment that would maximise benefits under different circumstances

Many factors can influence future flood hazard and flood risk and these can change over different timescales, the main factors are:

- Climate change –increasing intensity and frequency of storm events
- Population – large population growth and move towards living in cities. This can lead to urban expansion but also to increased density of population and gradual infilling of existing urban areas – both of which result in a change in urban land cover and loss of pervious surfaces thereby increasing surface water run-off and possible surface water flooding.

The impacts of this are:

- by 2080 57,000 additional homes could be at risk due to climate change (from all sources of flooding; 13,800 specifically from surface water flooding). (based on data in the 2015 FRM Strategies)
- by 2037 it is projected that 350,000 new homes may be built (from 2015 to 2037), the effectiveness of land use planning policy in avoiding flood risk to these new homes is important. (based on data from National Records of Scotland)

The loss of pervious surface in urban areas increases the risk of surface water flooding but the scale of this increase, and its impact on flood risk, is unknown.

Urban creep can be defined as areas that 'are already part of the urban fabric that have been subject to a change in permeability, e.g. paving over front gardens, or extensions to existing buildings'. This is different from the process of 'urban expansion' (also known as 'urban sprawl'), whereby the urban area expands into adjacent un-developed areas, and urban infill, whereby previously un-developed plots, within existing urban areas, are subsequently developed. The term 'urban creep' evolved in the late 2000s to account for increases in the density of urban land use and impervious surfaces through the paving over of green spaces. The impacts this has on urban catchment hydrology and urban drainage capacity is of particular concern in light of projected population growth and climate change.

This report details the methods and results of a CREW funded project to provide SEPA with potential methods for mapping urban creep (rate of urban creep and where it occurs) and some estimates of rates of creep for Edinburgh. The study methods have been designed following a literature review of urban creep mapping (Appendix 1) that looked at possible methods, including their accuracy, data and software requirements, cost-effectiveness, and reproducibility. The methods utilise high resolution aerial photography to map changes in impervious cover at the building plot scale – differentiating between new urban growth and urban creep. Upscaling of this mapping could provide more robust estimates of Urban Creep for Scotland. This report also provides some analysis of where urban creep occurred in Edinburgh, with some more spatially explicit breakdowns of observed rates according to housing type and age.

These results are important as:

- More detailed knowledge of observed rates of urban creep could allow projections to be made of future impervious ground cover in urban areas.
- Further work could identify how best to include projections of future urban creep and extent of pervious ground into SEPA's pluvial flood hazard and risk modelling and mapping to determine the impact of urban creep on future surface water flood hazard and risk.
- Knowledge of future surface water flooding will be improved by considering climate change and urban creep scenarios.
- Better knowledge of areas at risk and the factors influencing surface water flood risk, both now and in the future, will enable improved management and mitigation.

1.2 Research questions

Two objectives underlie this work:

1. To answer the question, what are the typical rates of urban creep for selected urban areas in Scotland?
2. To develop and test a transferable methodology for quantifying rates of urban creep.

2 Research Undertaken

2.1 Data sources

Three sets of aerial images were obtained for this study (Figure 1).

1) Getmapping™ 2015. This data set was obtained as a set of tiles, which were mosaicked. This data was already well georeferenced and rectified, and was used for the rectification of all other imagery. It was at a resolution of 25cm. It was obtained under a Scottish Government licence.

2) Landmap 2005. This data was obtained as an Enhanced Compression Wavelet (ECW) file from the NERC Earth Observation Data Centre (NEODC) repository and was licensed for research use. It was provided at 0.1m pixel size

3) Bluesky™ 1990. This data was scanned from aerial photography by Bluesky specifically for this project. It was provided at 0.1m pixel size.

Figure 1 Aerial photography for a region of Edinburgh for the study time periods.

Ordnance Survey (OS) Mastermap polygons (from OS Mastermap 2017) were used to provide a spatial framework to summarise the classified images against e.g. to identify buildings, gardens, roads and other features. The Landmap Cities Revealed data set (Landmap, 2014) was used to classify buildings and gave the age and type of building. The Landmap data set was created by manual interpretation of aerial photography. However, it only assigned building ages and building types to buildings, not gardens. To assign gardens to building categories the dominant building type was calculated for each of the units that Edinburgh is broken up into by the Copernicus Urban Atlas data set. This allowed gardens to be assigned to a building class, enabling the results to be analysed by building age and type. The unclassified class covers non-residential properties, but also buildings that could not be assigned to other classes by the interpreters of the aerial photography. The unclassified class differs between the building type and the building age classes, as it was easier for the interpreters to identify building type than building age. Figure 2 shows the area of land covered by different building types and age in Edinburgh, Figure 3 shows where the different buildings and gardens are in Edinburgh. Features that are not buildings, gardens or roads, e.g. rivers and parks (based on the OS Mastermap classification) were not analysed for rates of change in this research.

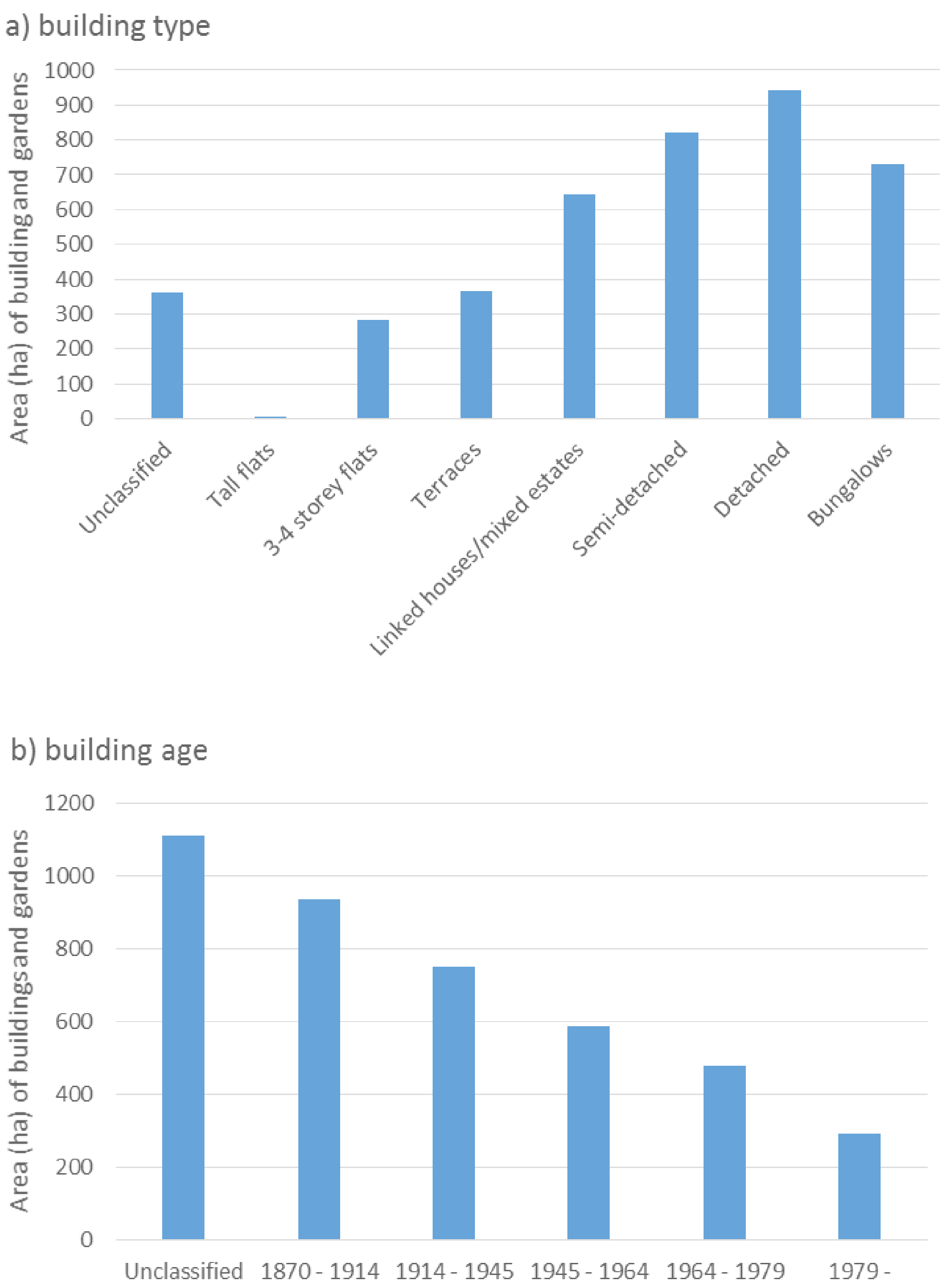

Figure 2 Area covered by different types of buildings in Edinburgh (includes building area and garden area) for a) building type and b) building age.

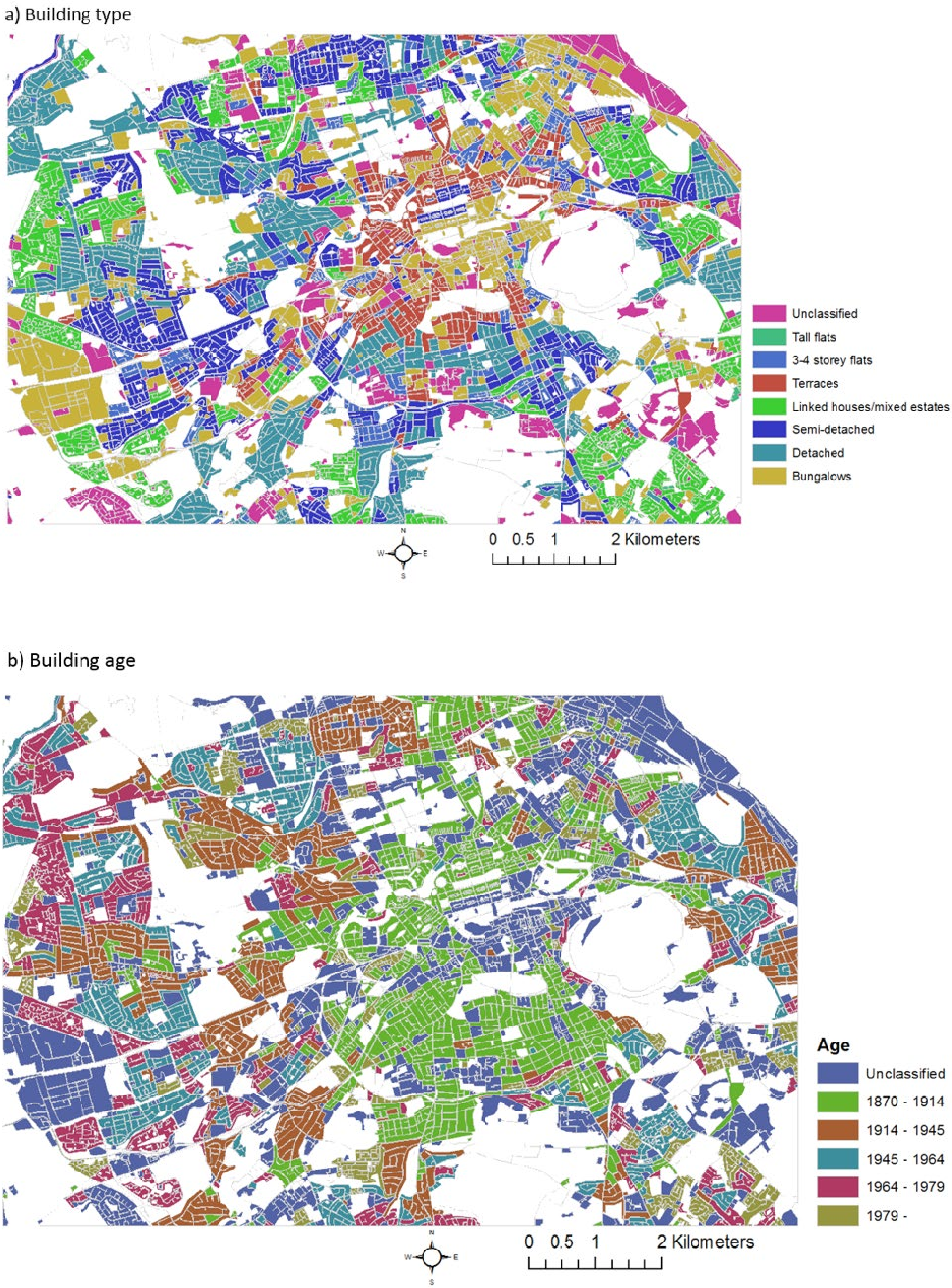

Figure 3 Map showing the dominant building and garden type (a) and age (b) for different areas of Edinburgh (areas are from the Copernicus Urban Atlas data set).

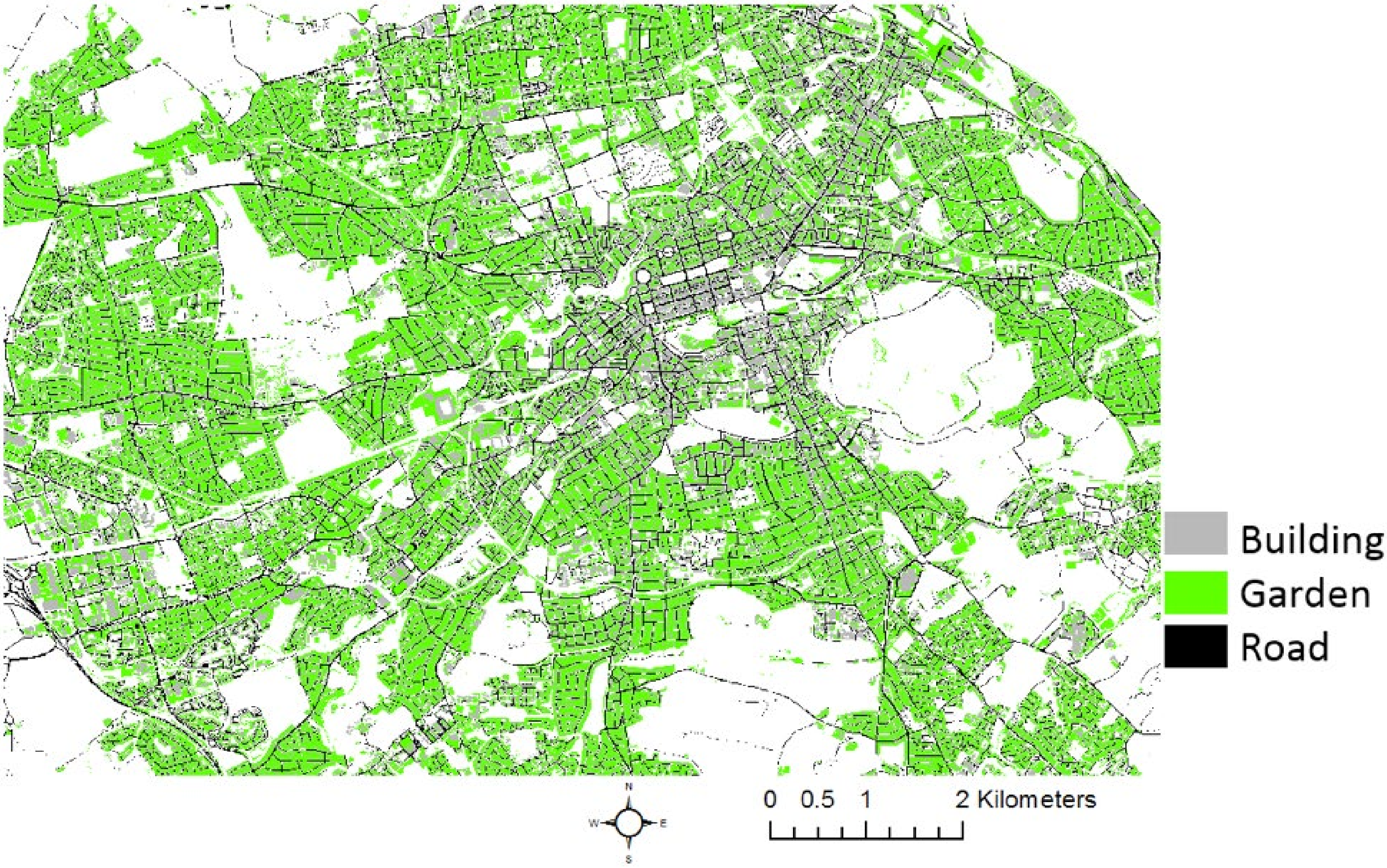

Figure 4 Areas analysed for urban creep, urban expansion, urban decrease and road expansion across Edinburgh. White areas such as parks and greenspace were excluded from analysis, because of issues with classification accuracy.

2.2 Area of Edinburgh mapped

The aerial photography was classified for a 12km x 8km area of Edinburgh (9,600ha). Arable areas and sea beyond the city were then removed from the analysis, as were land cover such as parks and greenspaces, watercourses and railways within the city. The greenspaces were removed because of problems classifying key areas of them correctly, especially Arthur's Seat where areas of bare rock were classified inconsistently for different years. This left an area of 4,4578ha that was analysed.

Figure 4 shows the areas analysed in this project, specifically, gardens, buildings and roads. Parks and greenspaces are in the final database and could be analysed in the future, however care would have to be taken to account for classification issues, for example by removing affected areas from analysis.

3 Methods

This section describes the methods developed to map urban creep and urban expansion. The key processing stages were geocorrection, segmentation, image classification and ingestion into the OS Mastermap polygons for additional processing and analysis. The classification was conducted with Random Forest. Random Forest is a machine learning algorithm that creates many decision trees based on subsets of the training data. The result is then produced from the most common result for each pixel. This approach makes Random Forest very robust and it has proven popular for a wide range of image classification problems.

3.1 Issues with image quality

The quality of the aerial photography varied between years, due to differences in acquisition year and date, and the view angle from the aircraft (a function of altitude and camera set-up). This caused differences in the amount and orientation of shadow, as well as affecting the degree of displacement of the tops of tall buildings (Figure 5). The apparent 'movement' of tall buildings complicates analysis of change between different dates, especially when buildings 'appear' to extend their OS building footprint. The quality of the photos is also affected by their spatial resolution, the way they have been stored and processed since being acquired, and the file format used for image storage. The 1990 aerial photography were the best images and were scanned from prints of the original photography specifically for this project. The 2005 photography had lower contrast than the 1990 and 2015 photography, possibly due to the

Figure 5 Column a) OS building footprint (yellow polygon) and aerial photos for 2015 (top image) and 1990 (bottom image). Column b) shows aerial photos for 2015 (top image) and 2005 (bottom image).

way the data has been processed, although this cannot be confirmed. The time of year when the photos are acquired affects the contrast between the different classes, which affects the segmentation and the classification. It has not been possible to identify key dates for acquiring data for image classification within this project, but essentially the greener the vegetation the greater the contrast between vegetation and impervious surface. These factors all combine to degrade the quality of the classifications and to complicate the analysis. The method documented here attempts to minimise these factors.

3.2 Data processing

Issues with data quality, especially those such as shadow, variable image quality, differing resolution and spatial registration may produce errors in mapping urban creep. To minimise the effects of these, steps were taken to improve the comparison across the three sets of aerial photography.

1) 1) Prior to analysis, the 1990 and 2005 data were georectified against the 2015 dataset, which was used as the reference dataset.

2) 2) All three datasets were processed at 0.1m resolution, which was the original resolution of the 1990 and 2005 data. The 2015 data was classified at 0.25m resolution, and then resampled to 0.1m for analysis.

3) 3) Data were generalised and tabulated to a common framework, with a 0.1m tolerance to ensure a good comparison of area statistics.

4) 4) Each tile of data was checked after classification to ensure that the urban, shadow and woody or herbaceous classes were broadly correct. If segmentation or classification problems were identified, the image enhancement and segmentation were revisited for that tile.

5) 5) Since shadow was variable across all three datasets, shadow was classified for each scene, and a common shadow dataset was generated. This was used to remove areas considered not suitable for analysis, across the three datasets to ensure a consistent analysis.

A breakdown of the full processing method is shown in Figure 6. This process was repeated for each year. To break the process into manageable sections, 4sq km tiles were chosen to avoid memory issues. In this way, six tiles could be processed on one machine. Separate machines were used

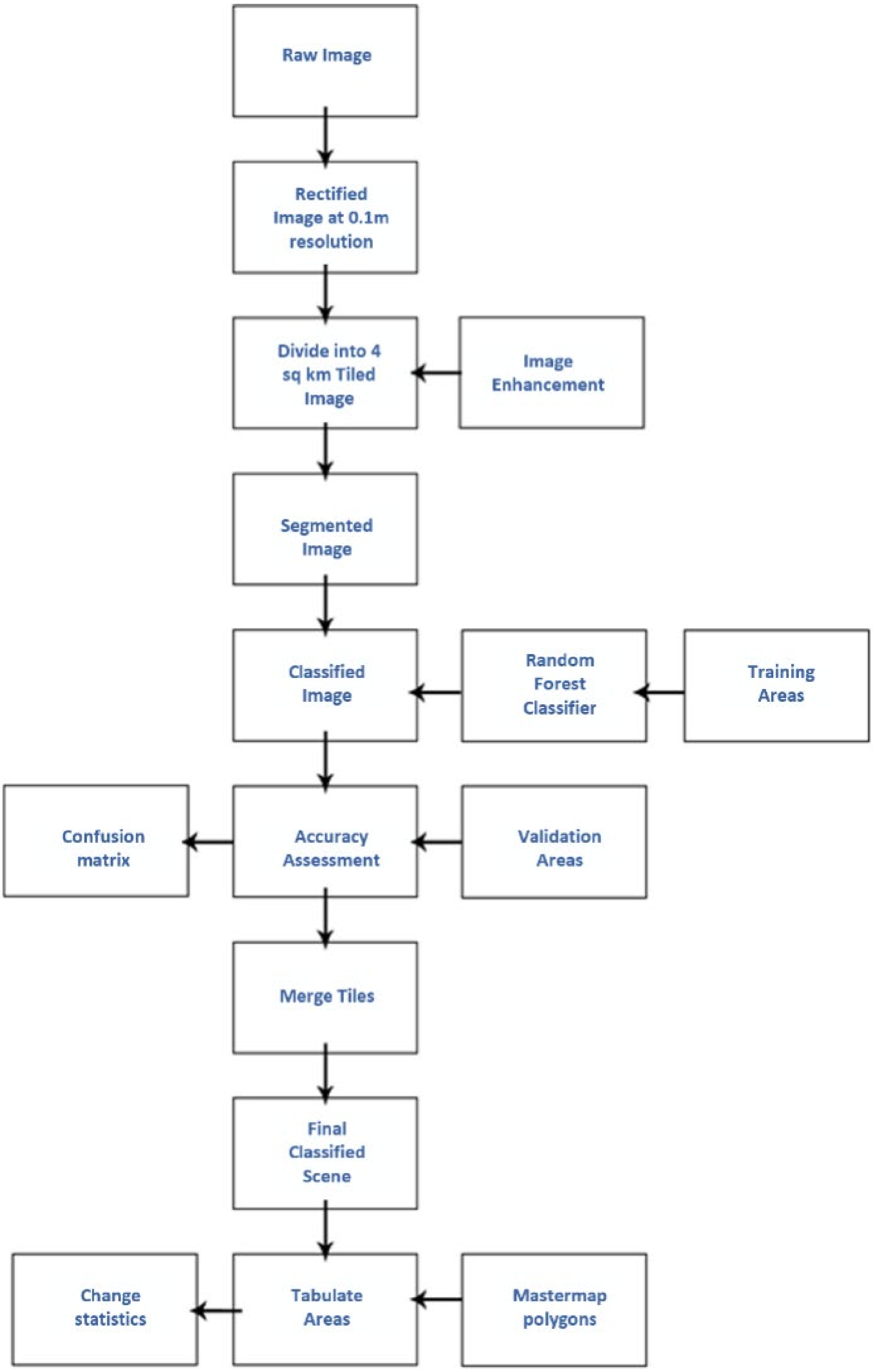

Figure 6 Flow diagram showing the sequence of processing steps to classify one year of aerial photography and summarised into the database.

for each year to reduce the length of time taken to process the data. This meant that if image enhancement was required, or adjustments to the segmentation, the process could continue uninterrupted on the remaining tiles until completion. The difficulties with image enhancement are due to the flight path of the aircraft on the day of image acquisition. Levels of light may vary given different levels of cloud cover, and therefore the scene may appear mottled or levels of brightness may differ across the scene.

3.3 Rectification (or georeferencing)

An initial review of the data showed that the aerial photos were not perfectly georeferenced. For example, the footprint of buildings appeared to move slightly between the different aerial photos. To compensate for this the data for 2005 and 1990 were georeferenced, to match the 2015 imagery. Initially, methods to automatically register the images were attempted but did not prove fruitful, and took a great deal of time. The images were therefore manually georeferenced. This involved manually identifying points that could be accurately identified in the 2015 image and the image being georeferenced, these manually identified points are called tie points. Tiepoints were located on ground surface features, rather than elevated features which moved due to the viewing angle of the aircraft. The best features for tiepoints include pylon bases, gravestones, and fixed objects such as piers and tennis courts.

Following rectification the data were clipped to the common extent of the three aerial photos, and the three aerial photos were subset (tiled) into smaller areas. Initially the data were converted to 1km tiles for ease of analysis and method development, although once the method was developed 4km tiles were used. Six 4km x 4km tiles cover the entire study area (Figure 7), resulting in 18 tiles to process for the three years.

Figure 7 The six 4km x 4km tiled areas for Edinburgh.

3.4 Contrast enhancement and Image Segmentation

Initial work classifying individual pixels produced poor classification results with high levels of speckle and misclassification. To avoid this a segmentation-based approach was explored. Segmentation divides the image up into clusters (or segments) of pixels of similar colour and gives the image a more homogeneous look (Figure 8a and 8b). Further development work showed that segmentation results were improved if the aerial photos had their contrast enhanced prior to segmentation (Table 1). These values were arrived at by sequential adjustment of the settings

Table 1 Values used for contrast enhancement.

Setting	Value
Contrast	30
Brightness	6
Gamma	0.79

a) Raw TIF image (0.1m resolution) prior to processing

b) Segmented Image

Figure 8 Processing details from raw raster image, to a segmented image.

followed by a resegmentation. This was repeated until maximum colour separation allowed urban areas and roads to be fully differentiated from the grass and tree-covered areas. The segmentation and contrast enhancement were performed within ArcGIS Pro using the Image Segmentation and Classification Toolbox in the Spatial Analyst extension. The segmentation was performed within Model Builder, so that the process could easily be repeated for each year.

3.5 Image classification

Classification was performed in ESRI ArcMap 10.4.1. The classification process has three stages, firstly; the identification of training areas; secondly; training of the classification algorithm; and finally, application to the image to produce the final classification. The training areas were selected within the segmented image using the classification overlay tool in ArcMap. The training areas encompassed contiguous areas that represented four classes: trees, grassland, urban and shadow. The random forest classification used the Random Trees Classifier in the Segmentation and Classification toolset of ArcMap. The 1990, 2005 and 2015 photos were all processed in the same way. However owing to the differing resolution, slightly different settings were used for 2015 (Table 2). From this point onwards the grassland and tree classes are considered as a single vegetation class.

The basic method involved producing an initial classification (Figure 9), then reviewing it, after which the training areas would be revised and the classification would be re-run. The classification would then be reviewed and either deemed acceptable, or revised further.

a) Segmented Image

b) Classified area (shadow, urban and vegetation)

Figure 9 Processing details, from a segmented image to classified image, in the classified image, shadow is black, vegetation is green and urban areas are brown.

Table 2 Settings for segmentation and random forest classification

Tool		Value for 1990, 2005	Value for 2015
Segment Mean Shift	Spectral Detail 1	20	20
	Spatial Detail 2	20	20
	Minimum Segment Size (pixels)	20	4
Random Forest Classifier	Max No. Trees	50	50
	Max Tree Depth	30	30
	Max Samples Per Class	1000	1000

3.6 Shadow removal

Shadow affected each of the years differently (Figure 10; Figure 5). Shadow is important as it creates areas where it is not possible to see what is going on and that we cannot classify into urban or vegetation. To enable a sensible comparison between different years it was therefore necessary to create a total shadow layer that showed pixels that were shadow in one or more years. The total shadow layer was then used to remove shadowed areas from the analysis. For example a shadowed area in 1990, would be removed from the 1990 data, as well as the 2005 and 2015 data keeping the area covered by the 'good' data consistent between the three images. Figure 10 shows how variable the shadow is between the different images and also how shadows change because the housing stock has changed.

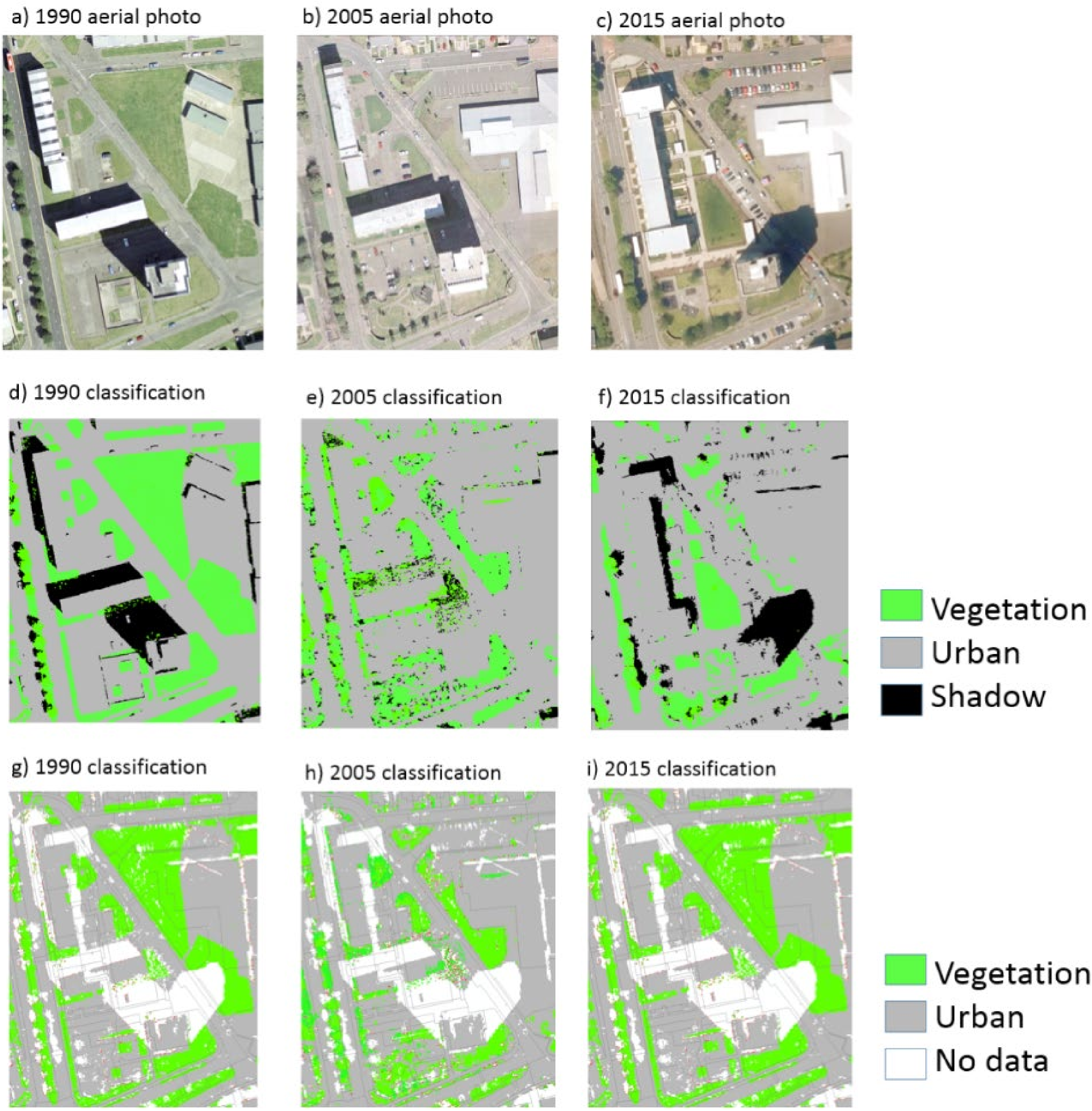

Figure 10 Example of shadow for a region of Edinburgh showing aerial photos (a-c), resultant classification (d-f) and classification with total shadow (across the 3 dates) removed.

3.7 Summarising using the OS Mastermap spatial framework

The classifications were summarised using the OS Mastermap polygons giving areas of urban and non-urban for each polygon for each year. This provided a flexible format for displaying and analysing the data, as it maintained all the existing OS attributes for the polygons, whilst enabling additional attributes to be added (Table 3). The key OS attributes were those providing a description of the polygon e.g. Building, Landform, Road or Track, and the Make column which provided information on the surface such as 'Manmade', 'Natural' and 'Multiple'.

3.8 Producing estimates of urban expansion, urban creep, urban decrease and new roads

The classified images contained a range of errors due to the quality of the aerial photography, the limitations of the spectral information for classifying into the required classes and the spatial consistency between the aerial photos. This meant that a simple comparison of the raster classifications was not very accurate. To compensate for the errors in the classifications, a series of queries were applied to the data. For example, to be identified as a real urban increase a polygon would have to show an increase in urban area above a specified threshold, these thresholds are shown in Table 4, e.g. to be counted as change in a garden >16m2 of land had to change from vegetation to urban (or vice versa). The use of thresholds allowed some of the classification errors and the spatial inconsistencies between data sets to be reduced.

From the database, estimates of urban creep, urban expansion, new roads and urban decrease (decrease in the amount of impervious surface) were produced. The queries in Table 4 show how the polygons were selected to identify the new roads and urban decrease. Table 4 also gives the queries for building expansion and garden expansion, which were intermediate in the production of the urban creep and urban expansion products.

Table 3 Attributes added to the spatial database. * indicates that there are similar columns for 2005 and 2015. ^ indicates that there are similar columns for '2005 to 2015' (labelled '05_15') and for '1990 to 2015' (labelled '90_15').

Attribute name	Attribute
Urban_90*	Area (m^2) covered by urban class in the 1990 classification
Forest_90*	Area (m^2) covered by forest class in the 1990 classification
Heb_90*	Area (m^2) covered by herbaceous class in the 1990 classification
TOTAL_90*	Total area (m^2) for the 1990 classification
PC_U_90*	Percentage of the polygon that is urban in 1990
DIFF_90_05*	Difference in percentage urban between '1990 to 2005'
SLOPE_90_05_15	Coefficient of the slope of a line through the amount of urban in 1990, 2005 and 2015 (in database but not used)
BUILDING	Result of a query identifying building objects in the OS database [1 denotes a building]
GARDEN	Result of a query identifying garden objects in the OS database [1 denotes a garden]
UE_90_05^	Urban expansion (FINAL PRODUCT)
UC_90_05^	Urban creep (FINAL PRODUCT)
BE_90_05^	Building expansion (intermediate product)
GE_90_05^	Garden expansion (intermediate product)
E_90_05^	Expansion (intermediate product, combines the BE and GE attributes in 1 column)
Road_90_05^	Road increase (FINAL PRODUCT)
UD_90_05^	Urban decrease (FINAL PRODUCT)
MC	Manual correction of errors (see attribute column for details)
Change_1990_2005^	Summary column giving type of change occurring in that polygon between 1990 and 2005.
No_change	Summary column. 1 denotes a building, road or garden not experiencing change.

Table 4 Thresholds for queries to identify polygons undergoing change. Names of attributes in the database are given in italics.			
Attribute	**Type of polygon applied to:**	**Polygon size criteria**	**Polygons meeting the following criteria:**
GE_90_05	Garden	>16m^2	Change in urban area that occurs in a garden > 16m^2 between 1990 and 2005 AND change needs to persist in the 1990 to 2015 data as a change in urban area of at least >14m^2
GE_05_15	Garden	>16m^2	Calculated after GE_90_05 and GE_90_15. Urban increase that occurs in a garden between 1990 and 2015, but not between 1990 and 2005, AND change in urban area > 16m^2 between 2005 and 2015 AND change in percentage urban is > 25% Plus, to avoid a systematic exclusion of older properties, urban increase between 1990 and 2015, but not between 1990 and 2005, AND change in urban area > 50m^2 between 2005 and 2015 AND change in percentage urban is > 10%
GE_90_15	Garden	>16m^2	Change in urban area that occurs in a garden > 16m^2 between 1990 and 2015 AND change in percentage urban between 1990 and 2015 > 10%
BE_90_05	Building	>6m^2	Change in percentage urban between 1990 and 2005 > 50% AND percentage Urban in 1990 < 20 OR change in percentage urban between 1990 and 2005 > 70%
BE_05_15	Building	>6m^2	Change in percentage urban between 1990 and 2005 > 50% AND percentage urban in 1990 < 20 OR change in percentage urban between 1990 and 2005 > 70% Has to be persistent: Change in percentage urban between 1990 and 2005 > 16%
BE_90_15	Building	>6m^2	Change in percentage urban between 1990 and 2015 > 50% AND percentage urban in 1990 < 20 OR change in percentage urban between '1990 to 2015' > 70%
Road_90_05	Road	na	Change in percentage urban > 60% between 1990 and 2005
Road_05_15	Road	na	Change in percentage urban > 60% between 2005 and 2015 AND change detected between 1990 and 2015
Road_90_15	Road	na	Change in percentage urban > 60% between 1990 and 2015
UD_90_05	Building or garden	>16m^2	Change in percentage urban between 1990 and 2005 < -25 AND persists in 1990 to 2015 data, applied to polygons where the OS attribute 'Make = Multiple'
UD_05_15	Building or garden	>16m^2	Change in percentage urban between 1990 and 2005 < -25 AND persists in '1990 to 2015' data, applied to polygons where the OS attribute 'Make = Multiple'
UD_90_15	Building or garden	>16m^2	Change in percentage urban between 1990 and 2015 < -25 AND urban decrease observed between 1990 to 2005 OR 2005 to 2015

The first stage in identifying the areas of urban expansion and urban creep was to identify garden polygons and record them as an attribute (Table3, Garden attribute), as gardens are not explicitly identified in the OS data (Figure 11). Gardens were identified from the OS data where the 'Theme' was 'Land' and the descriptive term was 'General Surface', or the 'Theme' was 'Land' and the descriptive term was 'Landform' but the 'Make' was not 'Natural'.

Figure 11 Identify garden polygons from OS data (buildings and roads are already identified in the data).

Figure 12 shows the key stages in the production of the urban creep and urban expansion estimates. The first stage was to identify building and garden polygons showing an increase in urban area (using the thresholds identified in Table 4), which were then recorded in the Building Expansion (BE) and Garden Expansion (GE) columns respectively (Table 3) (Figure 13). To identify areas of urban expansion, a spatial buffer of 25m was applied to all the polygons classed as building expansion. When the buffer zones exceeded 1ha the buildings and gardens within these areas were classified as urban expansion (Figure 14). Car parks within 100m of the buffer zone were also included as urban expansion, with car parks identified using the Open Street Map data set. Remaining areas of change were classified as urban creep (Figure 15). Road expansion was identified using the query in Table 4 and an example is shown in Figure 16.

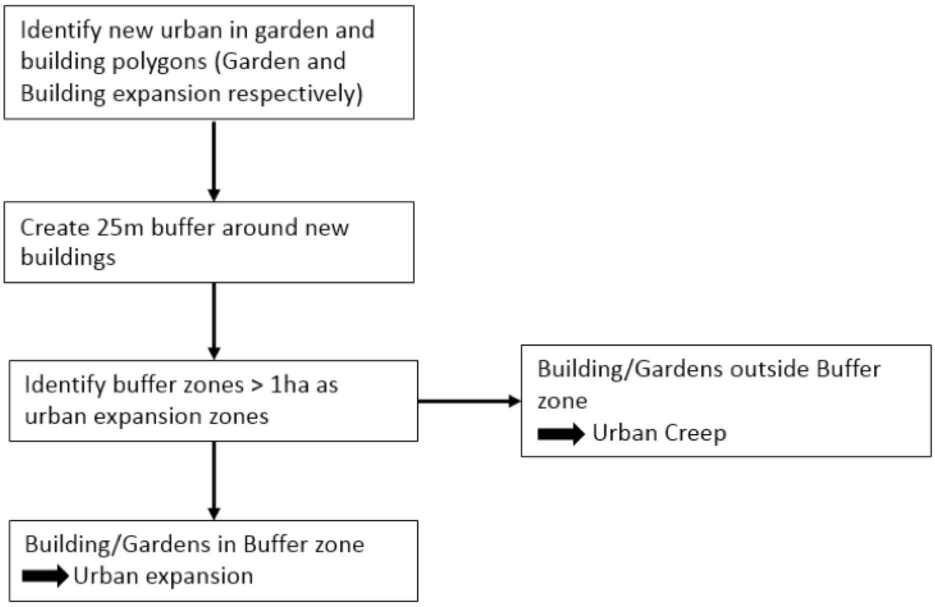

Figure 12 Overview of stages for estimating areas undergoing urban creep and urban expansion.

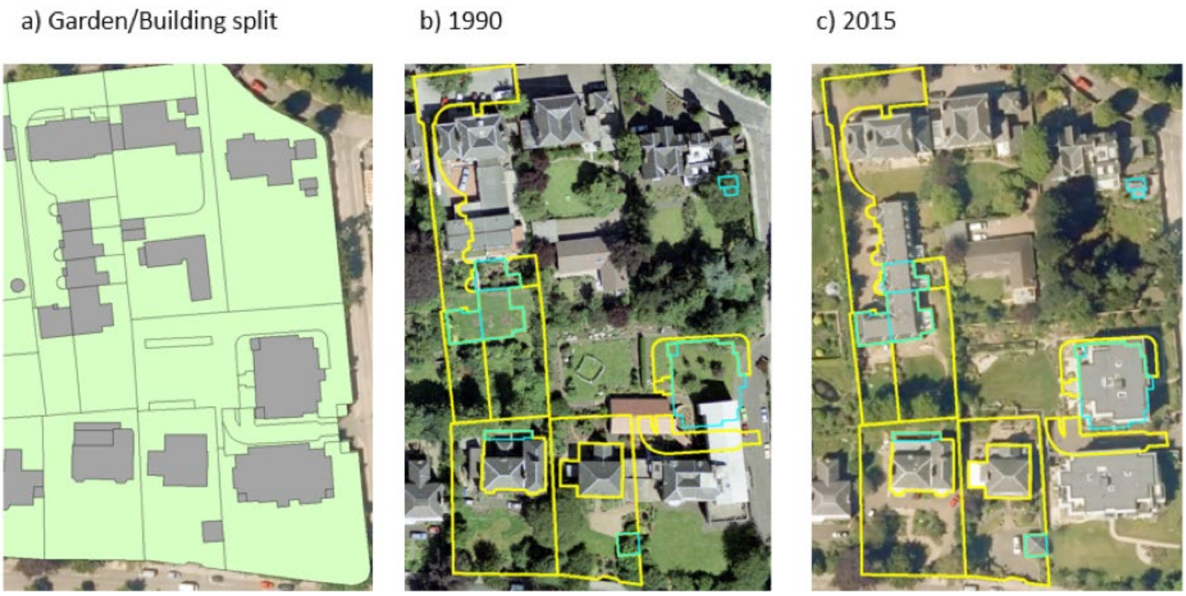

Figure 13 Identifying increased urban area in garden and building polygons. a) Shows the current building and garden split; b) shows the aerial photo in 1990, c) shows the aerial photo in 2015. Yellow polygons are garden polygons showing a significant increase in urban area between 1990 and 2015. Blue polygons are building polygons showing a significant increase in urban area between 1990 and 2015.

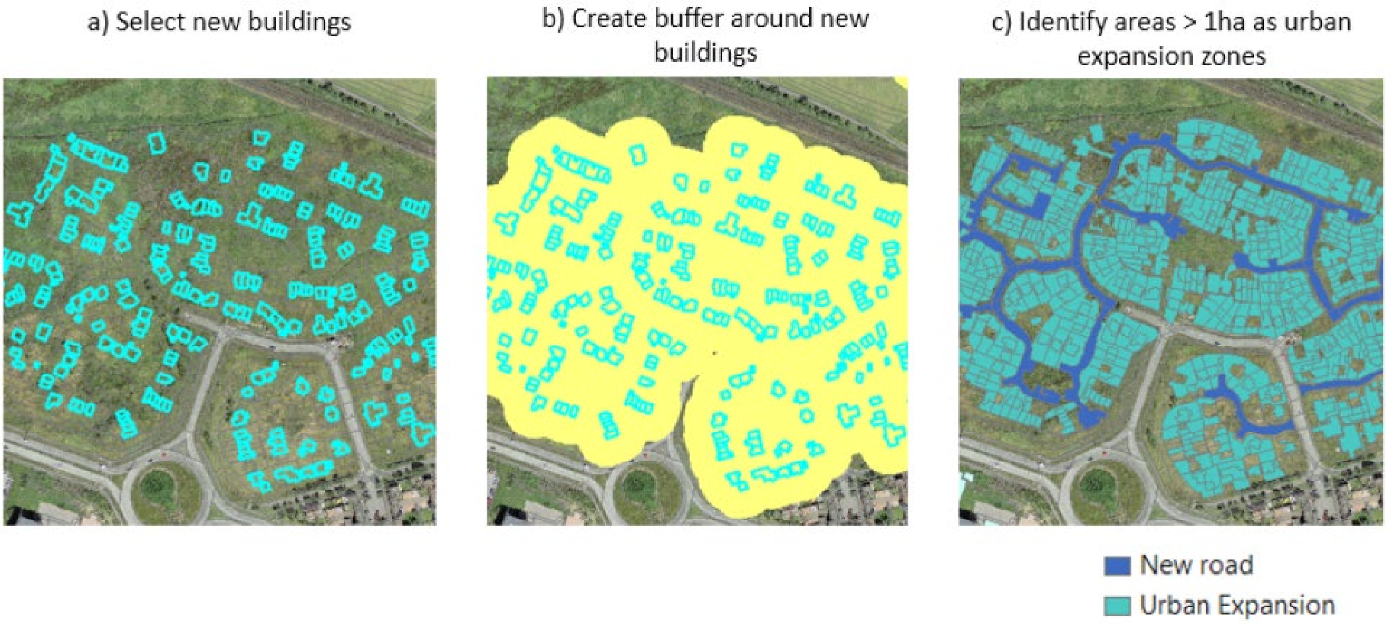

Figure 14 Identifying areas of urban expansion by a) selecting new buildings, b) creating a buffer zone around them, and c) identifying buffer zones > 1ha as urban expansion zones, and gardens and buildings within them as urban expansion.

Figure 15 Aerial photos for 1990, 2005 and 2015 with urban creep polygons showing urban creep occurring in gardens and building polygons for b) 1990-2005 and c) 2005-2015.

a) 1990

b) 2015

Figure 16 Example of road and urban expansion.

The four types of change identified are therefore:

Urban expansion – classified as large areas of urban development where the buffer zone exceeds 1ha.

Urban creep – classified as increases of urban area in building or garden polygons, which are not classified as urban expansion.

Road expansion – areas of new road. Typically, but not always, in areas of urban expansion.

Urban decrease –where the amount of urban area has decreased between the earlier and the later date. These areas are often areas of regeneration and include old industrial areas being regenerated as flats with gardens, so the urban area decreases and the vegetated area increases.

In Edinburgh, over the time period looked at in this study and for the area analysed, there is a lot of urban infill and urban regeneration, so the split between urban creep and urban expansion is not straightforward.

3.9 Validation results: classifications for 1990, 2005 and 2015

The classifications for 1990, 2005 and 2015 were validated using a stratified random sample of 200 polygons for each year. This gave 50 validation polygons each for urban and shadow, with 100 for the vegetation category as two classes (grassland and trees) were merged after the validation. In cases where there was uncertainty with manual determining the class of a polygon, the polygon was excluded from the validation. Consequently, the total number of validation polygons in is slightly less than 200 (Tables 5-7).The classifications were based on segments, and so the validation assessed whether the segments had been assigned the correct classification. Therefore, this validates both the area covered by the segment (i.e. that it is all one class) and that it is the correct class. The 200 polygons were manually reviewed to see whether they were correctly classified. The results were then summarised in correspondence (confusion) matrices.

Correspondence matrices are commonly used in the validation of categorical data, as they show which classes are getting confused with which other classes, and whether particular classes are being under or over-estimated. Values down the main diagonal are correctly classified i.e. the reference data and the classification both show the same class. Values off the main diagonal are misclassified. The correspondence tables are summarised by giving the ‘Producer’s accuracy’ and the ‘User’s accuracy’. The User’s and Producer’s accuracies are important tools for understanding the correspondence matrix and their respective roles are best illustrated by example.

The User’s accuracy shows how accurate the map is for a user on the ground, so for the 1990 classification 97.6% of the areas mapped by the urban classification are urban in the reference data (Table 5). The Producer's accuracy shows that there is some underestimation of the urban class as 18% of the urban reference samples are not classified urban. Essentially, this means that the areas classified as urban are really urban, but that overall urban area is being underestimated.

The classification results show that urban and vegetation are always classified with > 80% accuracy and often with > 90% accuracy (Tables 5-7). The 2015 classification shows the same pattern as 1990 for urban, with the User's accuracy being 93% and the Producer's accuracy slightly lower at 85%. Urban is classified with lower accuracy in 2005 than the other two years and this is probably due to the quality of the aerial photography. Vegetation is classified most accurately in 2005 and 2015, although for all three years there is some confusion with urban. Vegetation and shadow also get confused mainly because of the shadow that naturally occurs in and around tree canopies.

Table 5 Validation of the 1990 classification.

		Reference data				
	Class	**Urban**	**Vegetation**	**Shadow**	**Total**	**User's accuracy (%)**
Classification	Urban	41	0	2	42	97.6
	Vegetation	9	92	3	104	88.5
	Shadow	1	3	45	52	86.5
	Total	50	99	49	198	
	Producer's accuracy (%)	82.0	92.9	91.8		

Table 6 Validation of the 2005 classification.

		Reference data				
	Class	**Urban**	**Vegetation**	**Shadow**	**Total**	**User's accuracy (%)**
Classification	Urban	40	6	2	48	83.3
	Vegetation	7	82	0	89	92.1
	Shadow	3	11	46	60	76.7
	Total	50	99	48	197	
	Producer's accuracy (%)	80.0	82.8	95.8		

Table 7 Validation of the 2015 classification.

		Reference data				
	Class	**Urban**	**Vegetation**	**Shadow**	**Total**	**User's accuracy (%)**
Classification	Urban	41	1	2	44	93.2
	Vegetation	5	91	3	99	91.9
	Shadow	2	8	45	55	81.8
	Total	48	100	50	198	
	Producer's accuracy (%)	85.4	91	90		

3.10 Validation results: Estimates of urban change

To validate whether the areas identified as urban change were correctly identified, a stratified random sample of 250 polygons were selected for the five types of change (urban creep, urban expansion, urban decrease, new road and no change). The polygons were then manually reviewed to see whether they were correctly classified. If there was uncertainty about the correct categorisation of the polygon then it was excluded from the analysis and recorded as uncertain.

The results show that generally the accuracies are highest for the 1990-2015 change (Tables 8-10). This was expected as it does not involve 2005, which had the lowest classification accuracy for the urban class (Table 4). The accuracies for the different changes are mainly over 80%, with many having accuracies of greater than 90%. The results also show that user's accuracy for polygons classified as 'no change' are over 90%, but the producer's accuracy is lower at 59-78% (Tables 8-10). This suggests that no change is being slightly under-estimated. Tables 8-10 also show some confusion between Urban Creep and Urban Expansion, which is not surprising as the two different processes can be difficult to separate on some occasions.

Table 8 Confusion matrix for the urban changes 1990 to 2005

		Reference data							
	Type of change	Urban creep	Urban expansion	Urban decrease	New Road	No change	uncertain	Total	User's accuracy (%)
Database	Urban creep	41	5	1	0	2	1	50	84
	Urban expansion	1	44	2	0	3	0	50	88
	Urban decrease	2	0	36	0	6	6	50	82
	New road	0	0	0	48	2	0	50	96
	No change	3	0	0	0	47	0	50	94
	Total	47	49	39	48	60	7	250	
	Producer's Accuracy (%)	87	90	92	100	78	na		

Table 9: Confusion matrix for the urban changes 2005 to 2015.

		Reference data							
	Type of change	Urban creep	Urban expansion	Urban decrease	New Road	No change	uncertain	Total	User's accuracy (%)
Database	Urban creep	37	0	0	0	12	1	50	76
	Urban expansion	3	45	0	1	1	0	50	90
	Urban decrease	2	0	38	0	6	4	50	83
	New road	1	0	0	33	14	2	50	69
	No change	1	0	1	0	48	0	50	96
	Total	43	45	38	34	81	7	250	
	Producer's Accuracy (%)	86	100	100	97	59	na		

Table 10: Confusion matrix for the urban changes 1990 to 2015

		Reference data							
	Type of change	Urban creep	Urban expansion	Urban decrease	New Road	No change	uncertain	Total	User's accuracy (%)
Database	Urban creep	44	3	0	0	3	0	50	88
	Urban expansion	2	48	0	0	0	0	50	96
	Urban decrease	1	0	40	0	8	1	50	82
	New road	0	0	0	47	3	0	50	94
	No change	3	0	2	0	45	0	50	90
	Total	50	51	42	47	59	1	250	
	Producer's Accuracy (%)	88	94	95	100	76	na		

4 Results

4.1 Overall rates of change

Where hectares is noted, it relates to the actual amount of land coverage that has been modified from permeable to impermeable or vice versa. The maps showing where change has occurred however, use an Ordnance Survey derived unit of land (polygon) which shows those polygons where change was detected (i.e. not all the polygon will necessarily have changed).

In Edinburgh for the building, garden and road areas analysed (see section 2.2 for details), 281ha of vegetated land was converted to impervious surface between 1990 and 2015, at an average rate of 11.27ha/year (Table 11, Figure 17) (this includes all change including urban creep and urban expansion). 281ha is equivalent to 1.6 times the area of Arthur's Seat (170ha), or 20 times the area of Princes Street Gardens (13.9ha). The annual rate of loss, 11.27ha/year, is equivalent to about 15 football pitches (based on a football pitch area of 0.737ha). The results show that the increase per year was slightly higher between '2005 to 2015' at 10.30ha/year than for '1990 to 2005' at 9.67ha/year. The lower values for the rates between '1990 to 2005' and '2005 to 2015' are caused by several factors, including classification error and gardens with small rates of urban creep between both '1990-2005' and '2005-2015' that are below the change thresholds but are significant enough to be detected between '1990-2015'.

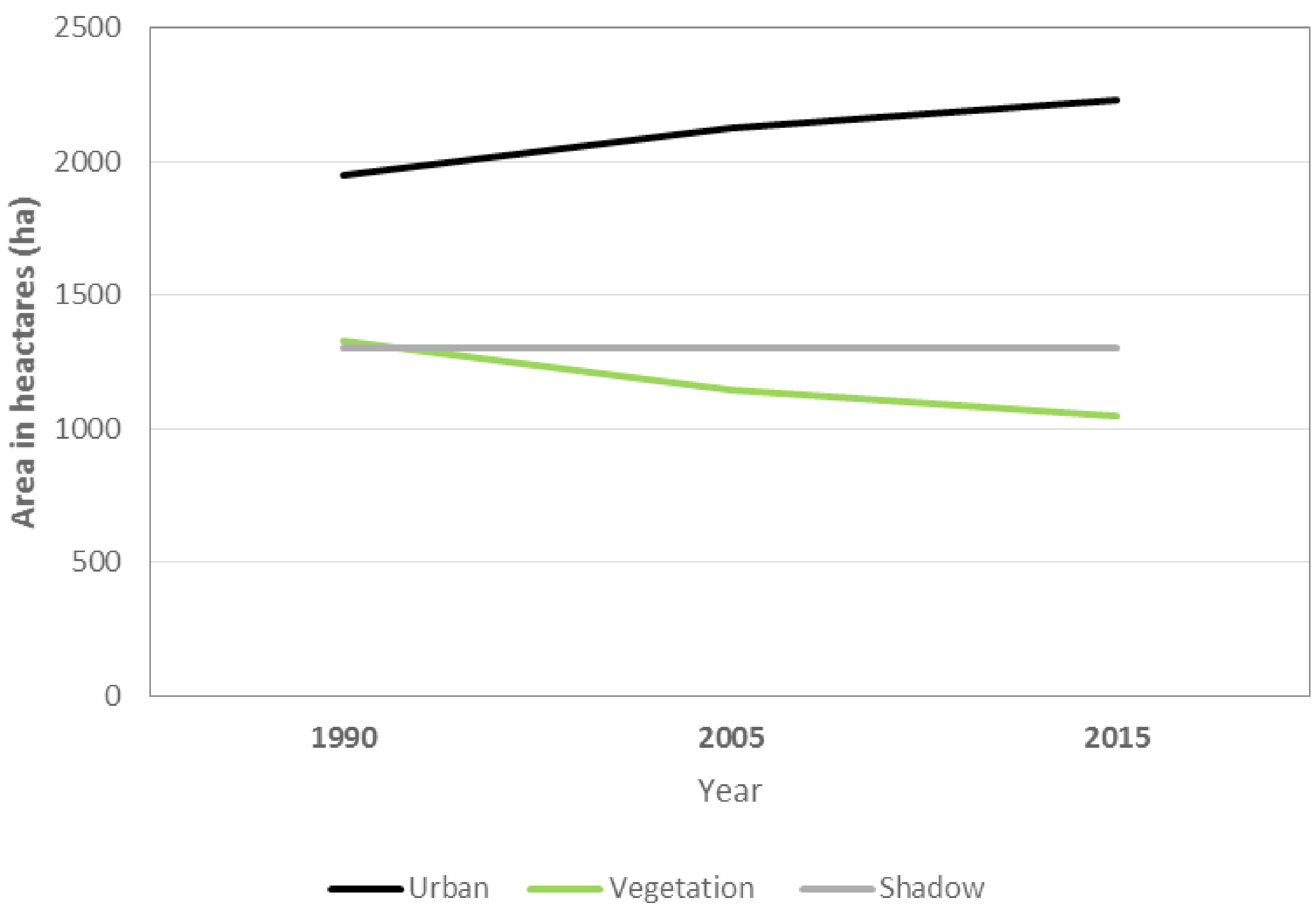

Figure 17 Trends in Urban, Vegetation and Shadow components between 1990 and 2015 for building garden and road areas analysed.

Table 11: Increase in urban area for each of the time periods. Values in hectares (ha).			
	1990 to 2005	**2005 to 2015**	**1990 to 2015**
Total impervious increase over time period (ha)	145.07	102.94	281.78
Rate of impervious increase (ha/year)	9.67	10.29	11.27

4.2 Rates of change according to type of change

In this section, the change in the urban area is assigned to either urban creep, urban expansion, urban decrease or new roads (Tables 12; Figure 18). The average annual rate of urban creep (excluding urban expansion) between 1990 and 2015 in Edinburgh is 6.44ha/year, this is equivalent to losing over 8 football pitches of vegetated land per year. The average annual rate of urban expansion between 1990 and 2015 is 4.81ha/year, this is the equivalent of losing more than 6 football pitches of vegetated land per year. Between '1990 to 2005' the rates of urban creep and urban expansion are 66ha and 82ha, or 4.4 and 5.5ha/year respectively. However, between '2005 to 2015' the rate of urban creep increases to just over 8ha/year (equivalent to the area of over 11 football pitches) whilst the urban expansion drops to about 2.2ha/year.

Urban decrease is the conversion of urban areas to vegetated areas and typically occurs when areas are regenerated. The rate of urban decrease (increase in vegetation) is higher between '1990 to 2005' than '2005 to 2015', affecting quite a small area - 27.63ha between 1990 and 2015. The area covered by roads increased by 28.36ha between '1990 to 2015', a relatively small area compared to the changes caused by urban creep and urban expansion.

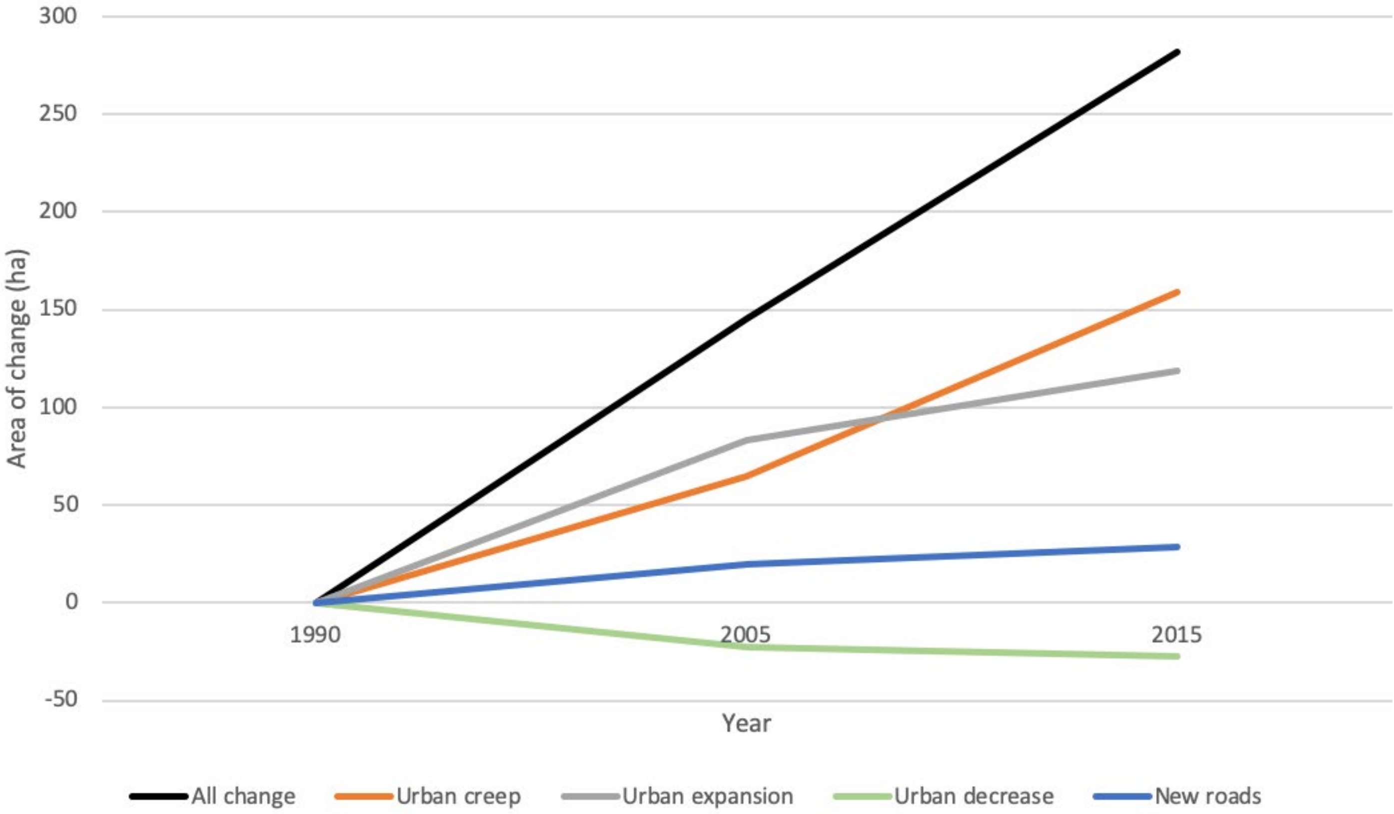

Figure 18 Magnitude of changes between 1990 and 2015.

Table 12: Extent of change between 1990 and 2015. [1]Calculated as a percentage of the total area of Edinburgh city covered by the aerial photographs, when the sea and arable land are excluded, which is 8903ha.

	1990 to 2005		2005 to 2015		1990 to 2015		
	Area of change (ha) (from vegetation to urban)	Rate of change (ha/yr)	Area of change (ha) (from vegetation to urban)	Rate of change (ha/yr)	Area of change (ha) (from vegetation to urban)	Area of change as a percent of Edinburgh[1] (%)	Rate of change (ha/yr)
All change	145.07	9.67	102.94	10.29	281.78	3.16	11.27
Urban Creep	66.20	4.41	81.90	8.19	160.90	1.81	6.44
Urban Expansion	81.80	5.45	22.03	2.20	120.15	1.35	4.81
Urban decrease	-22.58	-1.51	-6.54	-0.65	-27.63	-0.31	-1.11
New Roads	19.64	1.31	5.55	0.55	28.36	0.32	1.13
Urban Creep & Urban Expansion	148.00	9.87	103.93	10.39	281.06	3.16	11.24

4.3 Rates of change according to building age and type

Using the Landmap Cities Revealed data, gardens and buildings were assigned a building age and building structure class, allowing analysis of how the rates of change vary for different building types. The highest rates of urban creep are associated with detached houses (Figure 19) at 1.7ha/year with tall flats having the lowest rates (<0.004ha/year). Semi-detached houses and bungalows have urban creep rates of > 1ha/year. The breakdown according to age shows that unclassified buildings have the highest rates at over 2ha/year, followed by houses built between 1914 and 1945 at 1.51ha/year (Figure 20). The lowest rates are for houses built after at 1979 at 0.26ha/year.

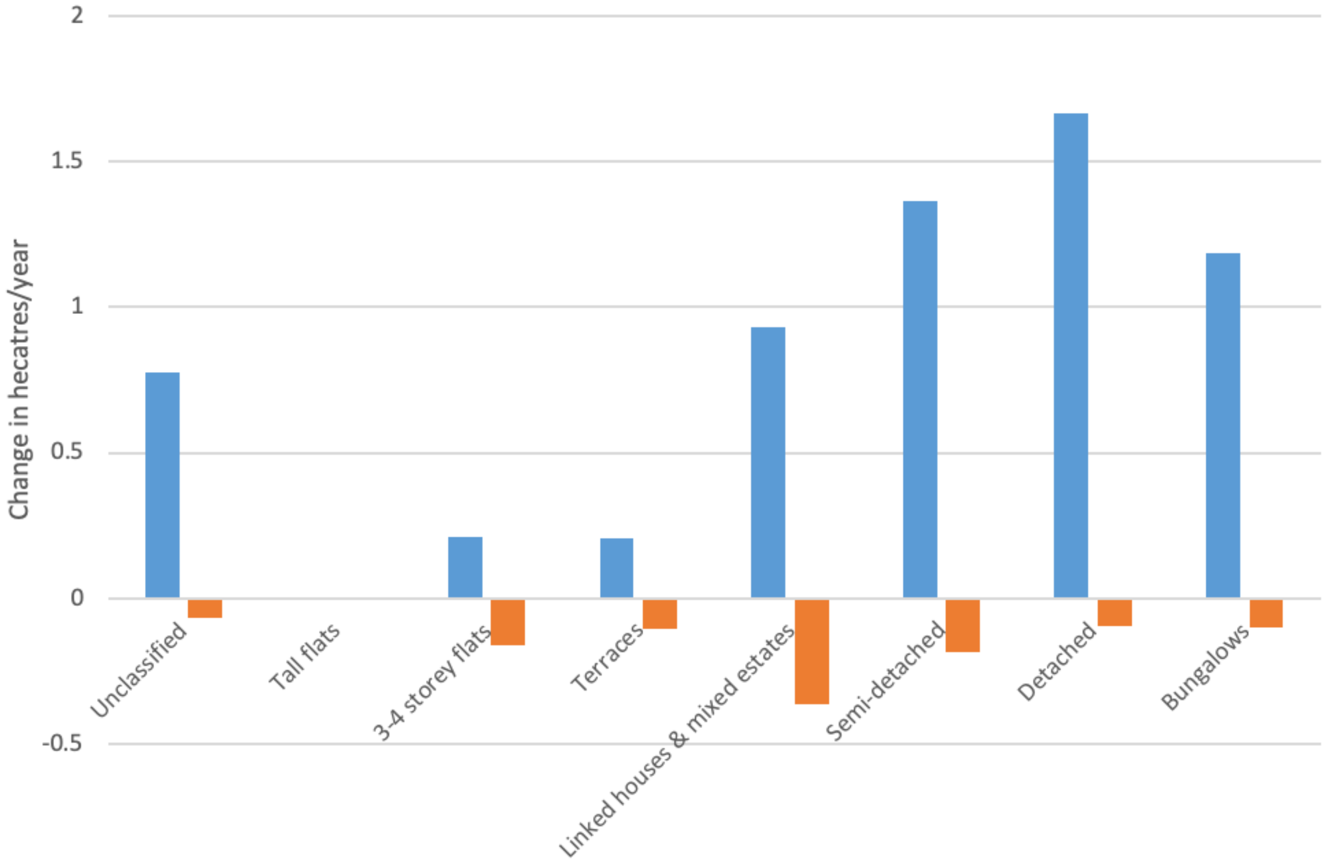

Figure 19 Average rate of urban creep between 1990 and 2015 for different types of building.

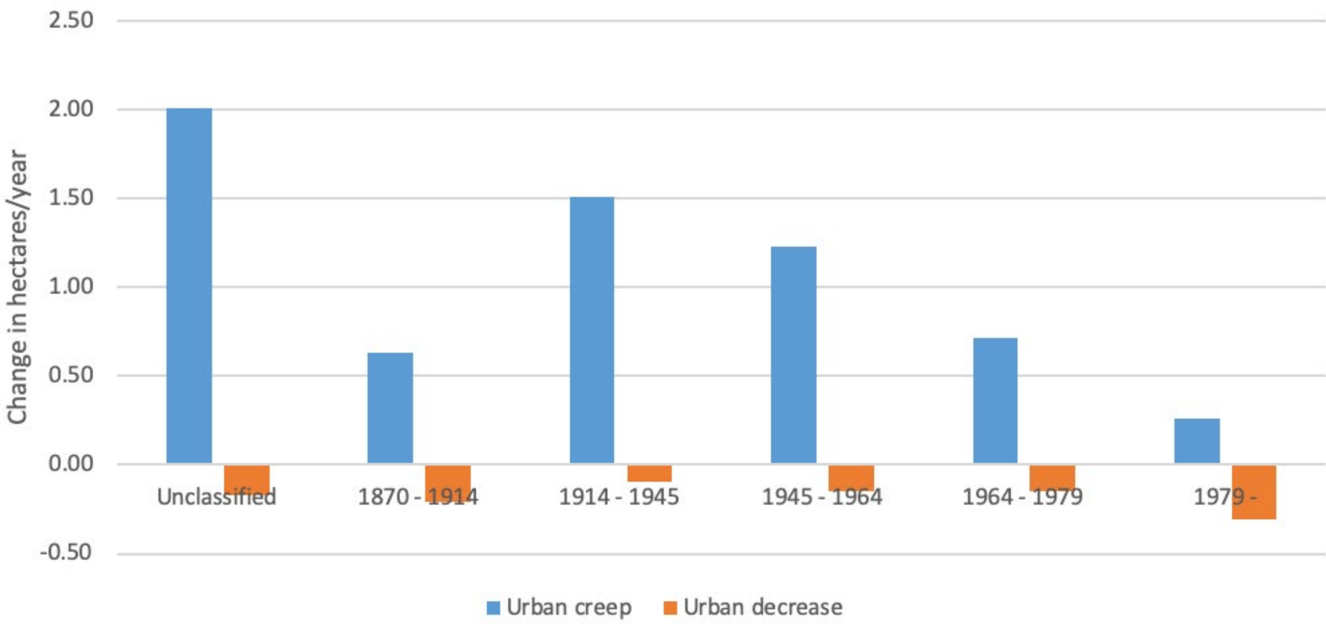

Figure 20 Average rate of urban creep between 1990 and 2015 for different ages of building.

4.4 Spatial distribution of urban change

Figure 21 shows the spatial distribution of polygons showing urban creep, urban expansion, urban decrease or new roads. The map is dominated by urban creep and urban expansion, with most of the change happening outside the city centre. The new roads are very narrow features, so do not show up in Figure 21. Urban creep is distributed widely across the city (Figure 22), whereas urban expansion is much more clustered (Figure 23). Urban decrease is also often clustered (Figure 24) and the larger areas are typically associated with urban regeneration and in some cases a move from non-residential to residential.

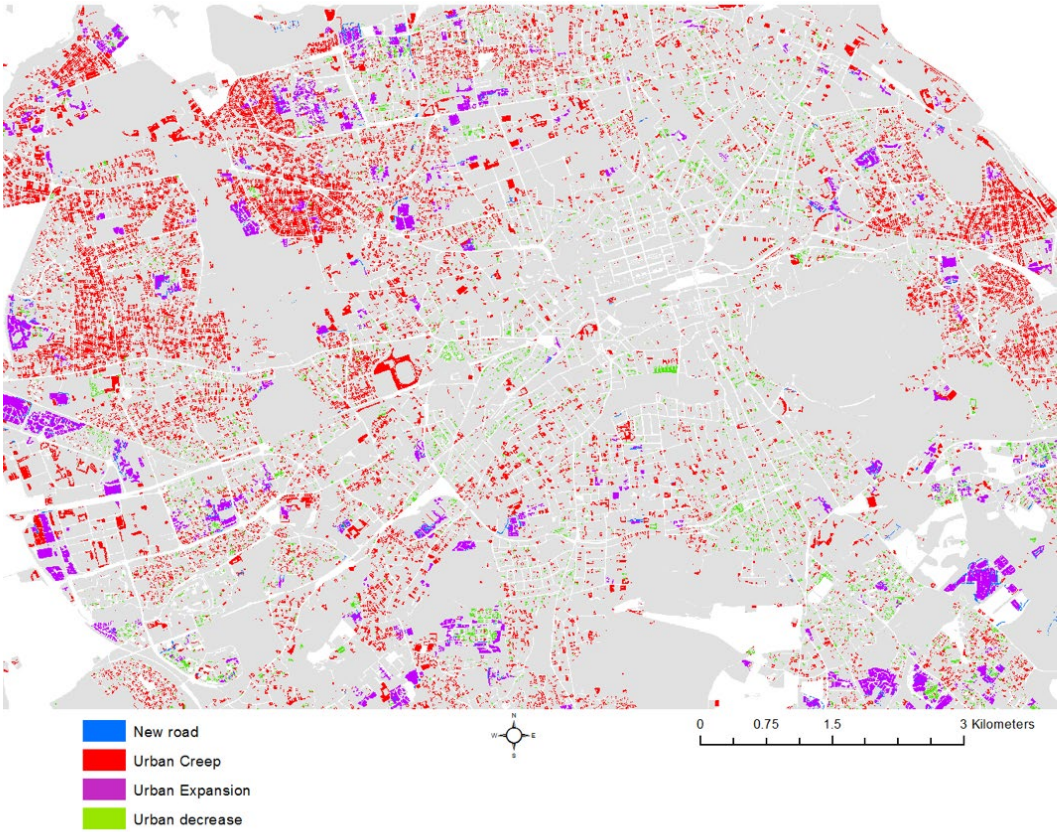

Figure 21 Polygons where some urban change was detected (not all the polygon will necessarily have changed) from the 1990 – 2015 data. Grey background and associated grey polygon outlines are areas of Edinburgh from EU Copernicus Urban Atlas.

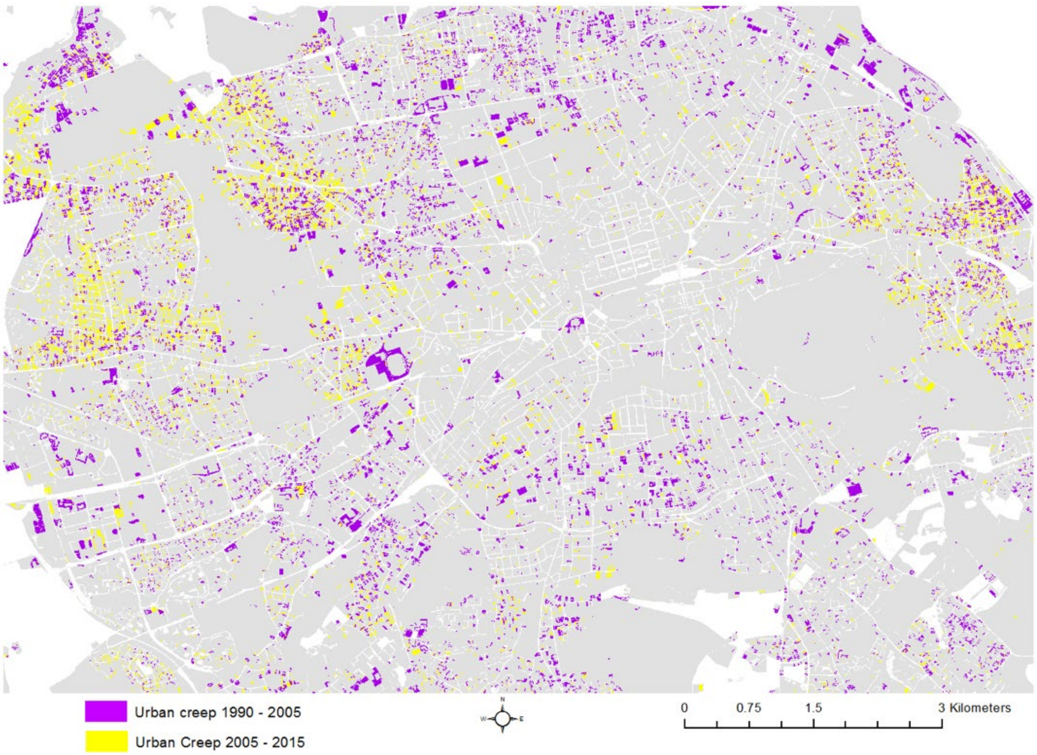

Figure 22 Polygons exhibiting urban creep between '1990 - 2005' and '2005 – 2015' (not all the polygon will necessarily have changed). Grey background EU Copernicus Urban Atlas.

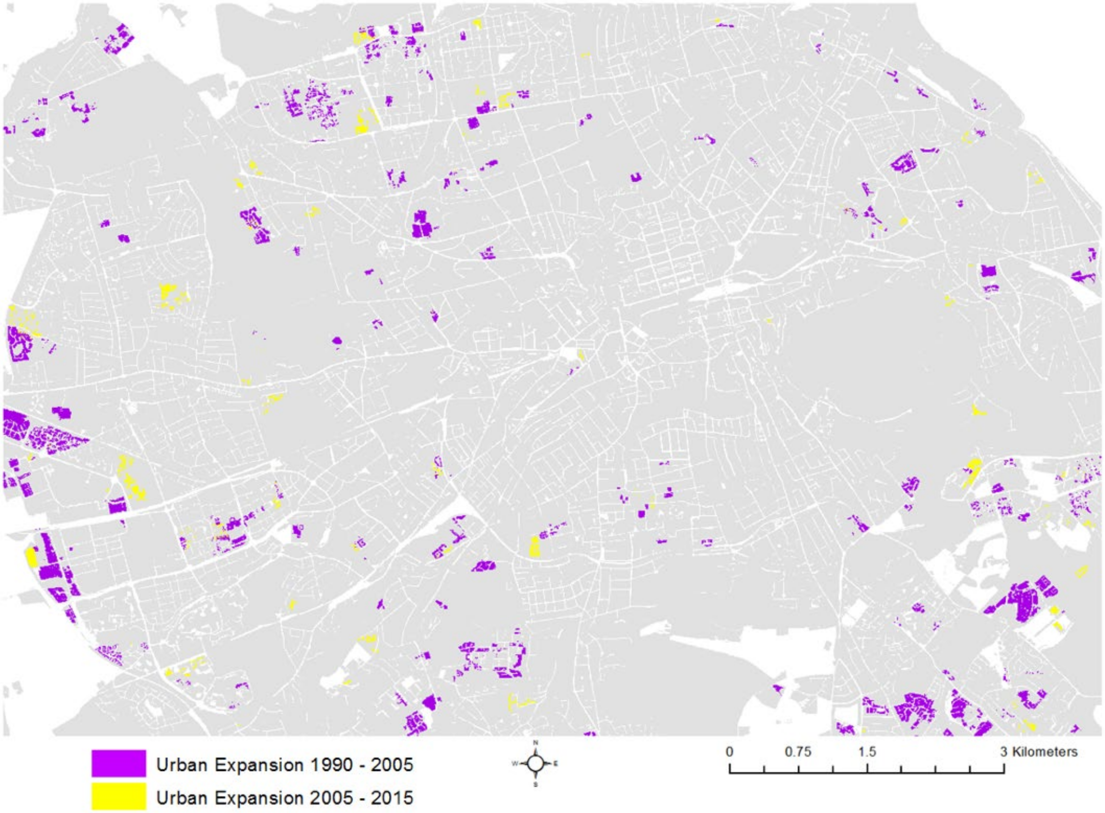

Figure 23 Polygons identified as undergoing urban expansion between '1990 - 2005' and '2005 – 2015' (note the polygons include garden and building polygons, so not all of this area is impervious). Grey background EU Copernicus Urban Atlas.

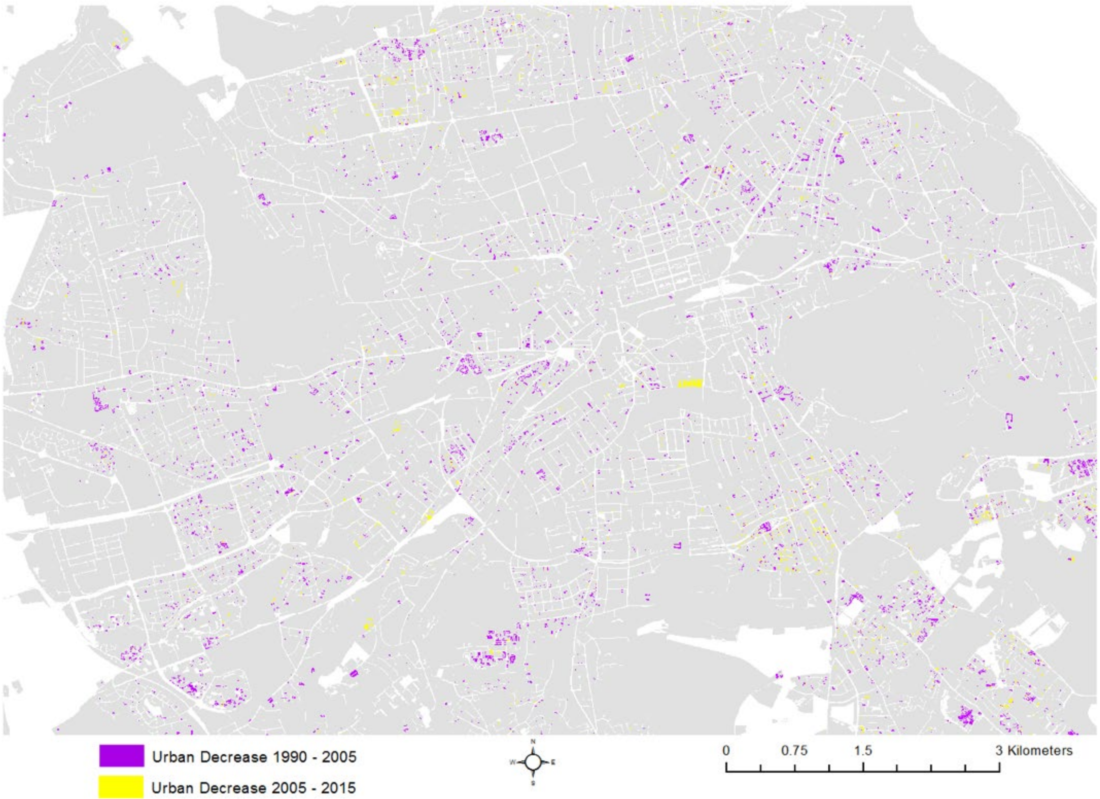

Figure 24 Polygons exhibiting urban decrease between '1990 - 2005' and '2005 – 2015' (not all the polygon will necessarily have changed). Grey background EU Copernicus Urban Atlas.

5 Main Findings

The main findings from this study are:

- Between 1990 and 2015 Edinburgh lost an average 11.27ha/year of vegetated land to urban land cover (from all types of change including urban creep and urban expansion). This is equivalent to losing over fifteen football pitches of vegetated land per year.
- The average annual rate of urban creep in Edinburgh (around buildings and their gardens and grounds), between 1990 and 2015, is 6.44ha/year. This is equivalent to losing over eight football pitches of vegetated land per year.
- The average annual rate of urban expansion in Edinburgh between 1990 and 2015 is 4.81ha/ year. This is equivalent to losing more than six football pitches of vegetated land per year.
- The highest rates of vegetation loss due to urban creep are for detached houses, which contribute on average 1.7ha/year of urban creep across Edinburgh. Semi-detached houses and bungalows also contribute high rates of urban creep of > 1ha/year.
- Flats and terraced houses have lower rates of urban creep with tall flats contributing the lowest rates of urban creep (<0.004ha/year) across Edinburgh.
- The maps of change show that urban creep is focused towards established peri-urban areas of the city and exhibits very low rates in the city centre. Urban expansion is clustered and located more towards the edges of the city.
- Where age of buildings is known, houses built between 1914 and 1945 contribute the highest rates of urban creep, at 1.51ha/year, across Edinburgh.

Methodological Findings

- A semi-automated processing chain can be applied to large amounts of aerial photography to produce estimates of urban creep and urban expansion. This process took some trial and error to develop, but can now be applied more quickly. There are however limitations due to the quality of the aerial photos. This was compensated for, to some extent, using the thresholds in Table 4, however, the process of refining the queries was quite slow, especially when compensating for the poorer quality data.
- The image classification results show that urban and vegetation are always classified with > 80% accuracy and often with > 90% accuracy.
- The quality of aerial photography is very variable between different years, with time of year, time of day, image angle, spatial resolution and image contrast all affecting the quality of the final classifications in a number of ways.
    - Image timing and angle affect the extent of shadow in the image, and as shadowed areas must be treated as "no-data", this limits the mappable area.
    - Spatial resolution limits the size of the smallest features that are accurately detectable and, where it differs between images, causes inconsistencies i.e. a path may be detected in one image, but not in the next image.
    - Images with good contrast are best. Image contrast varied between the images and in the 'washed' out images with low contrast - the segmentation and classification were less accurate (this affected the 2005 image most badly). Contrast enhancement methods were applied and were found generally to improve segmentation results, but they can only help when there is some spectral difference between the classes. They cannot convert poor contrast images to good contrast images, they can only improve the contrast very slightly.
    - For this project aerial photography had to be purchased for 1990. However, going forward good quality aerial imagery will be available nationally under the One Scotland Mapping Agreement (OSMA) and will be free for public bodies. This agreement started in 2010.
    - Spatial displacement of buildings occurs due to the angle of the photo and the height of the building, with apparent displacements of up to 10m for tall blocks of flats in Edinburgh. This creates an additional source of uncertainty, which will combine with other factors to reduce the accuracy of the classifications.
- New builds (e.g. large sheds or garages) are the smallest features that can be accurately detected, with a minimum mappable unit of 6m2. For change in impervious surface within gardens a threshold of 16m2 was set. With better aerial photography these values could be reduced.
- This project has created a very dense data set for Edinburgh that could be queried and explored for a range of further analysis, including where urban creep occurs, the factors influencing it and the impact of urban creep on pluvial flood hazard and risk.
- Potential further work on how this could be rolled out across Scotland has been proposed.

5.1 Next steps/Issues and way forward

5.1.1 Further analysis of data for Edinburgh

This project has produced a very comprehensive database for Edinburgh that can be used for a range of analysis beyond the scope of this project. For example:

Improving the definition of urban creep and urban expansion. The results here use a definition of urban expansion based on the size of areas of new build, specifically 1ha, so areas > 1ha were classed as urban expansion and areas < 1ha were classed as urban creep. This generally works well, however with data on drainage networks and run-off catchments it would be possible to analyse the data with more hydrologically relevant definitions of urban creep and urban expansion. So urban creep could be identified as new urban areas utilising existing drainage networks, whilst urban expansion could be defined as new urban areas utilising new drainage capacity. The structure of the main database means that it could be easily be reanalysed in this way. Separating urban creep, urban expansion, urban infill and urban regeneration is complicated, especially as different users may have slightly different definitions of the four processes. Further work would be required to develop methods to separate urban infill and urban regeneration, from urban creep and urban expansion.

Better identification of the type of urban or vegetated land. Using the OS Mastermap data enabled some analysis by OS attributes, so that some analysis could be done of where change was occurring. Because of the OS polygon attributes, it also allowed removal of features like railways and water from the analysis. The polygons however, are very small compared to the level of spatial error in the data set, so it may be that summarising by larger polygons, for example those in the EU Copernicus Urban Atlas, may have worked better. Larger polygons would have meant that the polygons were at a greater scale than the spatial uncertainty in the aerial photos. Using the OS Mastermap topography did have benefits however as it enabled the urban creep to be quantified at the property level from the classifications. Consequently, it could be assessed in future work to identify the rear and front of properties for isolation of garden areas from pathways and road verges. The OS greenspace data could be investigated to determine whether it would provide further information on the types of greenspace where loss is occurring. Analysis with the SEPA national flood risk assessment receptor data, which contains information on building type (residential and non-residential properties) could also be beneficial. Further analysis could also be done on where urban creep occurs and the factors influencing it. For example, more detailed analysis of the types of green spaces where loss is occurring and the types of areas where changes occurs including consideration of potential drivers of change such as social and economic factors, availability of car parking spaces etc.

Develop the validation work. The difference in angle of the capture of the aerial photography causes shifts in the apparent location of the buildings in the aerial photography. To compensate for this the OS Mastermap polygons were used as the basic spatial units for this work. Due to the error in the classifications, and the spatial error in the aerial photos, thresholds had to be set in the queries (Table 4) to help identify polygons undergoing the required change (urban creep, expansion, decrease or new roads). The thresholds were determined by exploring different thresholds and viewing the difference in the polygons selected. Overall, this process reduces uncertainty and is generally successful at identifying areas undergoing urban creep (Table 4), however refinements of the queries may produce improved estimates. Validation work is reported for the individual years at the segment-level for the classifications, and at the polygon level to identify whether the type of change has been correctly identified. Statistical methods exist (e.g. Olofsson *et al.*, 2014) that use the confusion matrix information (e.g. Tables 8-10) to calculate uncertainty intervals. Further work could explore this both for the segment-level validation work and for the identification of polygons as urban creep, expansion, decrease or new roads. This would also benefit from increasing the size of the validation samples and by having a double-validation i.e. two people checking each reference polygon to ensure that the reference data set is of the highest possible quality.

5.1.2 Areas of uncertainty

- In some cases, urban creep can be very difficult to identify from aerial photographs, because the contrast in the photo maybe poor; the images maybe poorly georeferenced; or areas may be obscured by shadows or tree canopies. These issues affect accurate identification regardless of whether urban creep is being identified manually or by some form of image processing. Mapping urban creep accurately is difficult.
- One of the assumptions underlying this work is that all urban creep is impervious, however, the type of surface used will have varying hydrological impacts, so the use of pervious paving will reduce the hydrological impact of urban creep.
- The shadow means it is difficult to determine whether a surface is impervious or vegetated, so these areas were removed from the analysis. This work has not assessed whether there is a systematic bias in this work caused by the under-sampling of urban areas in shadow. It is likely that most north facing properties will have been under-represented in this study.
- Large urban trees produce uncertainty as their canopies

may obscure impervious surfaces, so their growth, or removal, can cause apparent changes in impervious surface, when actually nothing has changed. In general tree cover from planting in 1990 or earlier will have increased by 2015, and therefore the level of "tree obscurity" would have increased accordingly Tree growth also affected the accuracy with which decreases in urban area could be detected, as some apparent urban decreases were caused by trees obscuring previously visible impervious surfaces. Cutting back of mature trees around roads also led to some existing roads being falsely identified as new roads.

- The quality of the aerial photography is critical in determining the quality of the final classification. The best photography will have high spectral contrast between vegetated and urban surfaces, as well as having low shadow and low displacement of tall buildings. Poor quality data takes more time to work with and still produces lower quality results.

5.1.2 Development work

How could this approach be scaled up to measure urban creep across Scotland?

Measuring urban creep involves both spatial and temporal dimensions. The temporal dimension is limited by the availability of suitable aerial photography or other data. Whereas the spatial component is more flexible, because of the complete coverage of aerial photography for Scotland that SEPA have access to, with several different assessment options for estimating urban creep across Scotland. The most comprehensive spatial solution would be to classify aerial photography for all urban areas in Scotland. This would be possible, but expensive and for small urban areas might not be necessary. An alternative would be a targeted assessment focussing on classifying and analysing aerial photography covering catchments where there is population growth or decline and different catchment types e.g. rural, urban, inland, coastal, east coast or west coast to provide figures representative of the different areas of Scotland.

What data sets are available that could contribute to this analysis?

Scottish Government have access to relatively recent aerial photography (currently from Getmapping), however, access to earlier aerial photography is also required if a historic baseline is required. For projects aiming to map Urban Creep and Urban Expansion going forward SEPA's access to existing aerial photography data will be sufficient. The 1990 aerial photography had to be ordered specifically for this project, so requiring this for all of Scotland could be expensive. The Land Cover Scotland 1988 (LCS88) land cover map was based on aerial photography for Scotland, so earlier data is available, but accessibility and licensing would need to be explored. The Landmap data archive (the source of the 2005 data used here) may have suitable data for other cities, although future work would need to adhere to the Landmap licensing requirements. For Edinburgh, the Landmap aerial photography data was found to have poorer image contrast, which resulted in poorer classifications. It is not clear whether this problem is limited to just the Edinburgh Landmap data, or whether it affects the Landmap data more widely.

Satellite data may have a role now and in the future, but not for the past, as the resolution is too coarse. The highest resolution data generally available for no cost is the 10m data of Sentinel-2, which should be sufficient to identify areas of urban expansion, although not for detecting small areas of urban creep. Alternatively, increasingly there are commercial high resolution satellite sensors with spatial resolutions of around 1m which would be suitable for detecting larger areas of urban creep. Some of the high resolution commercial satellites also capture information at more wavelengths, so may provide better quality, but lower resolution classifications that could be useful for urban creep mapping.

The EU Copernicus project has acquired Very High Resolution (VHR) satellite data (2.5m resolution) for major urban areas and produced an Urban Atlas, which maps different types of land cover. Although the Urban Atlas maybe useful over time for mapping urban expansion, it will not be useful for mapping urban creep. This is because the Urban Atlas uses high resolution satellite data to map blocks of cities and assigns different classes (e.g. continuous urban fabric, water, green areas) to each of the blocks, however the blocks are too coarse to identify urban creep (Figures 3, 17-20 use the Urban Atlas polygons). However, the 2.5m resolution satellite data, used to derive the Urban Atlas, maybe useful for mapping urban creep.

The EU Copernicus project also produces a time-series of impervious surface products, with the latest products being produced at a 20m resolution Europe-wide. These products will be able to detect areas of urban expansion, but further analysis would be required to determine to what extent they detect urban creep. Comparing the Copernicus Urban Atlas impervious surface products against this data set would show how well the Copernicus data detects urban creep and whether it can be used in practice.

OS Mastermap was a key data set for this project. OS Mastermap maps building boundaries and property boundaries, but does not provide information on the mix of pervious and impervious areas within land polygons. OS Mastermap provides more information than the OS greenspace layer, as the latter only covers publicly accessible greenspaces, not all of which are necessarily pervious, as buildings within greenspace are not mapped. Neither product gives the mix of impervious and pervious surface within the polygon that is required here.

SEPA has a dataset on receptors that could be impacted by flooding (e.g. residential properties, non-residential properties, roads, rail etc) that could be used to improve the classification of building types.

What would the resource implications be for rolling this out across Scotland?

To roll out the method developed in this project **for one** date for the next eleven largest cities/towns in Scotland (Table 13) would require about 44 weeks work for one person (i.e. create a 'baseline' using the getmapping aerial photography). This assumes that the aerial photography is available in a suitable format. To add an additional date would double the time required, as well as requiring an additional six weeks for data analysis, and a further six weeks for validation and some time for project management.

How frequently would any method be applied?

This study, and similar studies, show that rates of urban creep vary spatially and temporally. This makes it difficult to identify a fixed repeat frequency for assessing rates of urban creep. It may be that some key areas could be classified on a regular five-year time scale to provide an indication of general trends, with additional mapping being triggered by a range of factors, including:

- Rapid population growth
- Rapid increases in urban creep in the key areas that needed investigation over wider area
- Significant changes in catchment run-off response to rainfall events

The additional mapping could be broader in scale in the case of rapidly increasing urban creep in the indictor areas. Alternatively, it could be a focused analysis of individual catchments in the case of unexplained changes in catchment response, or population increases.

How might future developments affect our ability to map urban creep?

Image classification, especially of photography, is undergoing rapid development. Currently, large organisations like Google, Microsoft and Amazon are investing in, and exploring, methods to apply machine learning methods to automatically analyse, categorise and classify photography. Environmental science can potential benefit from these advances in machine learning. This means that it is likely that our ability to classify aerial photography will improve in the coming years as techniques evolve.

Follow-on modelling work

This study has the potential to inform a range of modelling activities, including identifying how significant urban creep is on pluvial flooding by comparing areas with low and high rates of urban creep and for investigating the impact of urban creep and expansion on run-off rates and flow paths and velocities.

It would be beneficial to use the SEPA pluvial model for Edinburgh and re-run it, incorporating this new information on ground permeability for 1990 and 2015 for chosen scenarios. The risk of flooding from these different scenarios could then be assessed, comparing them to determine the impact of changes in ground permeability on pluvial flood risk.

The first stage could be to look at observed rates of urban creep to determine if projections of ground permeability can be made based on the observed rates. This would need to consider how to take into account urban creep and urban expansion and what time periods to do projections for. For example, could the projections be made for the same time periods as the projections for climate change (e.g. 2030, 2050, 2080) and population change (NRS Scotland 2039).

Further work could explore how to incorporate projections of ground permeability into SEPA's pluvial flood hazard and risk modelling to assess future risk.

Table 13 Area and time required for rolling out to ten of Scotland's largest cities and towns for one date set of aerial photography.

	Approximate area (km^2)[1]	Number of 4x4km tiles	Time required
Glasgow	175	11	17 weeks
Aberdeen	65	4	6 weeks
Dundee	60	4	6 weeks
Paisley	27	2	3 weeks
East Kilbride	24	2	3 weeks
Livingston	27	2	3 weeks
Hamilton	16	1	1.5 weeks
Dunfermline	19	2	3 weeks
Cumbernauld	22	2	3 weeks
Inverness	21	2	3 weeks
Kirkcaldy	19	2	3 weeks

[1]Estimates of area are from different sources, so may not be directly comparable.

6 References

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Urban Creep studies in the UK and relevant studies to inform method development – An Evidence Review

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Introduction

Over 80% of the population in England lives in urban areas (ONS, 2014) and the population of the UK has risen from 32 million in 1901 to 66 million in 2017 (5.4 million in Scotland) (ONS, 2018). Significantly, the UK is one of ten countries globally with over 5% (5.7%) of total land area occupied by cities (Angel et al. 2011). It is set to undergo a period of extensive population growth to 74.3 million (15%) by 2039 (ONS, 2014) and extrapolated to 97.2 million (+53%) by the 2080s (Sayers et al. 2015). Concurrent with this growth is an overall increase in GDP and unprecedented growth in home value and related interest in adding value to homes. This has led to two outcomes: i) expansion of property footprint through extensions and conservatories (Allitt and Tewkesbury, 2009), and ii) additional impervious areas such as driveways and paving (Kelly, 2016). A particular relationship that is of importance is the link between on-street parking, public transport and car ownership, with a study in London (Greater London Authority, 2005) suggesting front gardens will be paved over if there is a lack of parking and that for every private space created one and half on-road spaces are lost.

The loss of pervious surfaces in existing developments through the progressive infilling of such surfaces and the expansion of the impervious footprint of existing properties is termed 'urban creep'. This is different to the process of 'urban sprawl', whereby the urban area expands into new un-developed areas (Sudhira et al., 2004), and urban infill, whereby previously un-developed plots within urban areas are subsequently developed, often as demand and value increase, and considered an antidote to urban sprawl (Mcconnell and Wiley, 2010). The terminology 'urban creep' is vague in origin but has evolved in the late 2000's out of specific consideration for increases in the density of urban land use and impervious surfaces through paving over of residential green spaces. The impacts this has on urban catchment hydrology and urban drainage capacity (e.g. Perry and Nawaz, 2008; Allitt and Tewkesbury, 2009) is of particular concern in light of projected population growth and climate change.
Increases in impervious cover and loss of pervious surfaces has long been acknowledged as drivers for increased surface runoff in urban areas through loss of infiltration capacity during storm events (Leopold, 1968). When this increase occurs in an existing area of development, with drainage designed for the original development footprint, this can lead to a lack of capacity in the drainage system for storm events, leading to what is commonly termed 'pluvial flooding' (Wheater and Evans, 2009). Pluvial floods typically occur during high-intensity short-duration (HI-SD) storm rainfall events (Miller and Hutchins, 2017) but could also be a result of blockages in the drainage system. Drainage in the UK is designed to a capacity calculated by assessing the probable rainfall event of a certain annual exceedance probability (AEP) under a range of rainfall durations to assess the critical duration – being the storm that generates the highest peak flow. Urban densification and inadequate drainage design have been primary drivers of pluvial and sewer flooding in the UK (Ofwat, 2011). Sewer flooding incidents have reduced with legislation (National Audit Office, 2004) but pluvial flooding is generally considered to have increased with population (Pitt, 2008). Detailed estimates of UK pluvial flood risk indicate approximately two million people are exposed to a 0.5% AEP risk (Houston et al., 2011). During the 2007 UK floods Environment Agency (EA) figures suggest two thirds of all flooding was due to inadequate surface water drainage systems (Pitt, 2008). In Northern Ireland a significant part of urban flooding is due to HI-SD rainfall overwhelming ageing drainage systems (Rivers Agency, 2011).

The English Flood and Water Management Act (FWMA) 2010 requires new developments to have surface water drainage plans with capacity for the 1% AEP – also known as the 1 in 100 year storm event (Defra, 2011) and utilize sustainable urban drainage systems (SuDS) to limit runoff to the natural 'greenfield' runoff rate (Defra, 2011). In Scotland, Scottish Planning Policy (SPP) states that new developments should not be at risk from pluvial flooding in the 1 in 200 year rainfall event and that rain and surface water run-off should be managed by SuDS. The Scottish Water Sewers for Scotland documentation stipulates that surface water drainage systems are designed such that flooding shall not occur during the 1:30yr event (Scottish Water, 2015). To account for the potential impact on pluvial flooding in new developments in England and Wales the EA set out an allowance that factors in an additional 10% increase in impervious extent in the design of drainage management (EA, 2013) also set out in BSI Standards Publication 8582 (BSI, 2013). The Flood Risk Management (Scotland) Act 2009 (FRM(S)A) was passed by Scottish Parliament in 2009 and transposes the EU Floods Directive 2007/60/EC into Scots Law, with new and extended duties on SEPA for managing flood risk. The same 10% allowance is currently used in Scotland (Scottish Water, 2015). There is uncertainty over whether this value is a robust measure of urban creep suitable for planning future flood risk and what are the hydrological impacts of urban creep on urban areas.

In Scotland it has been found in a study of urban creep in Edinburgh by Wright et al (2011) that the installation of impervious hardstanding is widespread and warrants measures to discourage continued development. The authors found that this was supported by public perception, but this itself was not backed up by households planning to reduce impervious areas of their property. Further, they found that the challenge is how to promote pervious hardstanding, which requires change to existing legislation and improved stakeholder perception to be effective.

This evidence review aims to assess the available evidence base pertaining to urban creep in the UK and has two main objectives: i) what are the methods, data and findings of studies into urban creep in the UK, and ii) what other methods and data could be applied to mapping urban creep? This will be used to inform development of suitable methods for the mapping of urban creep in Scotland.

Table A1: Studies of Urban creep

Source	Location	Time period	Method	Data Type and Resolution	LUC Finding	Accuracy	Hydrological impact
Allit and Tewksbury (2009)	5 UK cities (Leicester, Maidstone, Chester, Norwich, Newcastle-upon-Tyne)	Leicester - 1999 and 2006 , Maidstone - 2003 and 2006 , Chester - 2003 and 2007 , Norwich - 1999 and 2006, Newcastle-upon-Tyne - 2002 and 2007	Change mapping - Undertaken by Infoterra using data stack in object orientated classification system, Sampling - whole area and smaller sub areas, using building footprint sampling and period length to estimate annual property rate	Change mapping - GeoPerspectives AP, Sampling - Mastermap, Address point data, Sewer records postcode boundaries, soil maps, ACORN data, Property age data Resolution: 0.25m	Average rate of urban creep 0.75 m^2/house/year, max (Chester) 1.09 m^2/house/year, min (Newcastle) 0.38 m^2/house/year.	Accuracy of 95% reported for differentiation between impervious and pervious. No overall accuracy or uncertainty presented.	Not assessed.
EU Copernicus Urban Atlas	Europe-wide, but just for major cities	2006, 2009, 2012, 2015	Analysis of 2.5m satellite data	Urban Atlas polygons are the size of estates or blocks of housing.	Not analysed. The urban atlas data us likely to be suitable for Urban Expansion. However, the 2.5m satellite data that the Urban Atlas is derived from may be suitable for mapping urban creep.	unclear	Not assessed for UK
Greater London Authority (2005)	London	1999 - 2004	Change mapping using sample areas (14) - aerial photography and land use maps. Exact method not detailed. Also used data on applications for pavement crossovers 1999 -2004	Aerial photographs and land use maps. Resolution: unclassified	Total areas of front garden paving is 32km^2. Detailed change over study period not provided.	NA	Not assessed.
Kelly (2016)	UK - theoretical modelling study	NA	Utilized variable impervious fractions to model hydrological impact of increased impervious cover on theoretical garden.	Theoretical imperviousness scenarios with UKCP09 climate change data. Resolution: unclassified	Theoretical.	NA	Increased imperviousness directly correlated to increases in runoff.

Table A1: Studies of Urban creep							
Source	**Location**	**Time period**	**Method**	**Data Type and Resolution**	**LUC Finding**	**Accuracy**	**Hydrological impact**
Perry and Nawaz (2008)	Leeds, UK - 1.16km² area of suburban housing.	1971-2004	AP mapped to MM (2002) using manual delineation of polygons and classified.	AP - 1971 imagery (b&w) from Meridian Airmaps Ltd, 2004 imagery from Google Earth Resolution: 60cm pixels	13% increase in impervious surfaces, 75% of which due to paving gardens, 10% new development.	Manual delineation accuracy of 98%. Impervious area believed to be underestimate of true size.	L-THIA model predicts runoff increase of 12% in average annual runoff over study period.
Haddock, Brewer and Miller (2015)	Swindon - various hydrological catchments within the Haydon Wick peri-urban development	1990 - 2000 - 2010	Fishnet line-grid and manual grid cell count. Further classification made by building type. Creep vs new development recorded.	AP, OSMM (2010), Impervious raster (Miller & Grebby, 2014), Building type (Goss, 2014) Resolution:0.5m	Average urban creep per decade variable from 31 m²/decade (3.1m²/yr) to 61 m²/decade (6.1m/yr). Driveways (46%) and patios (45%) largest contributors. No correlation between property footprint and creep.	90% confidence interval, 4% error.	Variable increases in 100-year summer flood event from 0.9% to 5% over 1990-2010. Clear correlation between urban creep and increases in runoff (R^2 0.96)
Houston et al (2011)	UK wide, with more detailed studies in Belfast Glasgow, Wigan and Luton.	Current (2001)- 2050s	Uses population data and projections	ONS population estimates and UKCP09 climate data. Resolution not applicable.	Only used population as proxy - no detailed estimates of creep or urban expansion.	Not classified.	An additional 1.2 million people in urban areas could be put at risk by 2050 from a combination of climate change (300,000) and population growth (900,000).
London Wildlife Trust (2010)	London	1998/99 - 2006/08	Land cover was determined by comparing colour aerial photographs overlaid by garden boundaries from OS MasterMap topography.	Aerial photography and OS MasterMap. No detail on resolution.	Total vegetated land in London gardens 22,000ha - 57% of area. Average of 6m2 vegetation lost from every front garden and 11m2 from every back garden. I total 3,000ha of gardens lost in study period - 12% reduction.	Not classified	Not assessed
Ofwat (2011)	100 sewer network models covering 16% of England and Wales population.	2010 -2040	Applied urban creep estimates from UKWIR - applied relative to population growth projections (16.2%) and property density derived from address points.	ONS population estimates. UKWIR urban creep rates. Address points. Resolution: property.	Urban creep varied from 0% to 14% across study networks.	Not classified.	Urban creep leads to an increase in sewer flooding, with a median increase in 1:10 year event flooding of 11.5%.
Royal Horticultural Society (2006)	UK Wide study	2005	Commissioned survey into covering of front gardens - method unclear.	Not clear.	Range of front garden coverage - from 14% in London to 47% in NE England.	Not classified.	Not assessed.
Trioulet (2012)	Cranbrook catchment, London, UK.	2010 +10, 20, 30 years.	ArcGIS used to determine property number per sub-catchment and applied creep rate of 0.7m²/house/year - taken from UKWIR study (average)	Not detailed.	Estimated rate of 0.7m²/house/year leads to urban creep increase of 1.4% (10yrs), 3% (20yrs), and 4.1% (30yrs)	Not classified.	InfoWorks drainage model indicates peak flow increase of 6.2% in 30 years, increase in runoff volumes of 8.2%, and 28% increase in flooded locations.

Table A1: Studies of Urban creep							
Source	**Location**	**Time period**	**Method**	**Data Type and Resolution**	**LUC Finding**	**Accuracy**	**Hydrological impact**
UK Land Cover Map Series	UK	1990, 2000, 2007, 2015	Classification of satellite imagery	Polygon-based product, polygons are too large to detect urban creep	None	None that's relevant for Urban Creep	None for Urban Creep
Wright (2010)	Three residential areas of Edinburgh, Scotland.	2009	Walking and postal survey	Survey data Resolution: na	78%, 81% and 72% of the surveyed areas have modified driveways (average 77%). 49%, 63% and 72% of the surveyed building curtilages have increased the area of hardstanding in their driveway and/ or front gardens since initial construction (average of 61%). 64%, 57% and 47% of the surveyed building curtilages have replaced their pervious garden (lawn) or partially pervious driveway (gravel/ slab) and/or front garden with totally impervious materials since initial construction (average of 56%). Increase of approx. 9600 m^2 associated with such modifications, an average of 23 m^2 per curtilage.	Not classified	Not assessed
Wright et al. (2011)	Three residential areas of Edinburgh, Scotland.	Not defined.	Residential hard standing walking survey including >600 properties and a postal survey questionnaire.	Survey data. Resolution: na	Variable increases in impervious area from front garden modification from 14.3m^2 to 17m^2. 56% of front gardens paved over.	Not classified.	Not assessed.

Urban creep – methods, data and findings

There are few empirical studies that have researched and proposed robust estimates for rates of urban creep and associated impacts on flooding within the UK. A Royal Horticultural study (Society, 2005) found a wide range of figures for coverage of front gardens, with estimates for percentage of front gardens that are three-quarters paved varying from 14% in London to 47% in North-east England – but methods are unclear and accuracy uncertain. Walking and postal surveys of Edinburgh revealed variable rates across three residential areas but with an average of 77% of buildings having modified driveways since construction, and on average 56% of building curtilages have replaced their pervious lawn/driveway with impervious materials post construction (Wright, 2010). Both studies point to the high number of residential properties that have converted the visible pervious areas of the property to impervious surfaces.

Limited studies exist that employ detailed mapping of change, but a detailed study by Allit & Tewksbury across five UK cities revealed variable rates of urban creep and an average of 0.75m^2/house/year.
Other studies employ theoretical changes, with Kelly (2016) finding that runoff is directly proportional to impervious cover and rainfall intensity and that flood risk contribution is dependent upon soil type. This highlights the potential scale of impacts that paving front gardens alone poses. What such studies do not however provide, are detailed estimates of rates for urban creep that can be robustly applied in stormwater drainage design and future planning to cope with real-world urban creep.

This section details an evidence review of the available literature and reported figures to provide an overview of the scale of urban creep how it varies by region and development type, and what accuracy can be applied to reported findings. The studies we identified that quantify urban creep and related hydrological impacts are detailed in Table A1 and are discussed in this section.

Summary of reported findings

We identified studies that have undertaken research into rates of urban creep and associated hydrological impacts within the UK (Table A1). There is no consistent method or data applied across the studies and no consistent form for reporting on rates of urban creep or hydrological impact. Despite this, several points can be observed that summarize the available methods and reported data on urban creep:

- There is no consistent method or data applied across studies – with methods varying from manual to semi-automated object-orientated change analysis, based on data varying from ground survey to aerial photography.
- Only one primary study mapped true urban creep using semi-automated process (Allitt and Tewkesbury, 2009)
- Most studies are assessing change post 2000.
- No consistent form for reporting on rates of urban creep but tendency to break down wider results to household level using ancillary data on housing, such as MasterMap.
- Hydrological impacts include increased runoff, volumes, peak flows and incidences of sewer flooding.
- Hydrological impacts are assessed using hydrological models, with no empirical studies utilizing hydrological monitoring, and findings are not reported in a consistent manner.
- Of those analysing rates of urban creep these varied from 0.4m2/per house/yr (Newcastle: Allitt and Tewkesbury, 2009)) to 6.1m2/per house/yr (Haydon Wick: Haddock et al. 2015) across the areas studied.
- Most urban creep is from paving over of gardens, particularly at the front of properties for driveways.
- New development (infill) within existing areas can be a significant contributor and while not directly considered urban creep per se, it does constitute additional impervious surfaces and therefore an extra burden for drainage infrastructure, particularly as such single properties will not be required to have SuDS.
- Accuracy is poorly assessed and reported across the studies.
- There are a couple of satellite-derived products, including the UK Land Cover Map series and the EU Copernicus High Resolution Layer Impervious Surface product. They are too coarse to map urban creep, but may be useful for mapping urban expansion.

Change mapping methods

This section details the methods used in the available literature detailed in Table 1 to map fine scale changes in urban land use. This is broken down into the three methodological approaches: manual, semi-automated, and proxy methods.

Manual methods – manual delineation of change in property footprint

Manual methods may be used to delineate properties using multiple sets of spatially registered aerial photographs. This is a highly labour intensive process and can be prone to error, particularly if vegetation cover obscures the edges of the property footprint and the underlying hard standings. Overlays of linework may be used, such as the Ordnance Survey Mastermap products, but these are generally only available for the most up to date linework; it is unusual to find historic versions of this kind of data. Another issue that may arise is the spatial accuracy of such digitization. Unless the aerial data is extremely accurate, there are risks that the variation of georectification of the two sets of images may result in digitization errors. Manual methods using visual analysis of aerial photographs are popular in the studies assessed, and are employed by both Perry and Nawaz (2008), Haddock et al (2015), and Greater London Authority (2005). Haddock et al (2015) also used a walking survey for ground truthing the mapping of urban creep, and such a walking survey was also used by Wright et al. (2011) (also Wright, 2010) to support questionnaire results. Haddock et al (2015) note some key weaknesses of using such manual interpretation methods, including: subjectivity of image interpretation by user, variation in quality of images, and using assumptions that new surfaces are 100% impervious. For all such methods there is also the significant requirement for manual processing, which is not readily repeatable and is costly in terms of time.

Semi-automated methods – change detection using image classification

Image classification methods are now well developed and freely available as open source code, or implemented within software such as ENVI, ArcGIS or in software tools such as Matlab or R. These approaches require some level of supervision, and ground truth data obtained through survey work. Surprisingly only one of the studies identified has employed semi-automated methods for detecting change in aerial imagery, that being Allitt and Tewkesbury (2009) whose study was used to inform a UKWIR funded study into urban creep. This points to the technical difficulty in mapping such fine resolution change. Other research that has used the reported findings from this study to assess the hydrological impacts of creep include Trioulet (2012) and (Ofwat, 2011). Allitt and Tewkesbury (2009) summarized that the use of remote sensing technology to detect urban creep was successful and allowed large areas to be assessed. What is less clear is just how accurate the change mapping is. The processing was undertaken by Infoterra using LandBase™ land classification maps – however the authors note this 25cm scale product has a 95% accuracy.

Proxy methods

An alternative to manual or semi-automated methods are those that use estimates from building footprints and address-point data, planning application information, or information from questionnaires and model the rate of urban creep using established published rates of creep. This may be the best approach where aerial imagery is unavailable, or the use of such imagery is prevented due to other factors, such as vegetation cover, cloud cover or poor spatial registration. Studies using such methods included Wright et al. (2011) combining walking survey with postal questionnaire, and Houston et al. (2011) who used population projections along with reported rates of urban creep. While neither study discusses accuracy both approaches have a cost-effective and fast way of providing some estimates. There is however considerable uncertainty over how realistic such methods are for providing quantitative values for urban creep, as they are by default, only proxy methods and incorporate no specific quantification of urban creep for the area of interest. Such methods should not be used to inform quantitative studies on the impacts of urban creep.

Mapping urban change – potential image classification-based change mapping methods suitable for mapping urban creep

There are a range of related definitions to cover mapping urban change, from sprawl to expansion, all carried out at a range of scales and across urbanization types. From such studies assessing urban change we can identify a range of characterization methods that could be suitable for the mapping of urban creep. Urban creep can be measured in relative and absolute scales just like any form of urban change, as defined in Bhatta et al (2010). Indeed many metrics and statistics have been used to define and quantify the sprawl, often based on the granularity of the remotely sensed data that drives the quantification methodology. The selected approach should therefore consider the granularity of the remote sensed data, and the potential metrics that are to be produced for urban creep quantification. The techniques employed to estimate the final metrics are diverse, object oriented techniques using e.g. eCognition V5.0. This uses a multiresolution segmentation approach which is basically a bottom-up region-merging technique starting with one-pixel objects (Mathieu et al, 2007), through to machine learning techniques using for example, random forest classification (Reynolds, 2017), or support vector machines (Xu, 2017). The main problem associated with the classification of urban areas, is that tree canopies may cover impervious surfaces leading to the underestimation of urban extent. However, this is an issue that affects manual interpretation of aerial photos too; it can be minimized by using aerial photos when the deciduous trees have no leaves or by applying infrared imagery. Hybrid image classification methods can help if both vegetation and impervious surface are visible, as hybrid methods provide a final 'fuzzy' classification where the degree of membership to each land-use/land cover is given for each object. For example Jacquin (2008), used an approach based on a supervised classifier (e.g. standard nearest neighbour) and fuzzy logic. There are therefore a wide range of methods currently available, and the final approach in this study should rely not just on the data availability, or the final metric to be defined, but also on the availability of the final methods and data to the end user for subsequent future mapping of the study areas. Open source methods are therefore likely to be a strong factor in the selection of the approach.

Ji et al (2009) explored spatial analytical methods to identify both general trends and patterns of urban land changes using a supervised maximum likelihood classification and achieved good levels of user and producer accuracy with overall accuracy in the range 85 to 90%. Muhs et al (2016) also achieved high levels of accuracy (93 to 97%) using automated delineation methods for urban areas. One issue that does arise when delineating urban areas is that certain heterogeneous land classes can be more unreliable than others, due to spectral dissimilarity amongst training and validation areas. Huang et al (2016) demonstrated that urban delineation could be improved by separating the classified urban and non-urban classes using a majority voting rule, and then proceeding with a multiple classification. Thapa et al (2009) explored the effects of alternative approaches to urban mapping accuracy, they examined four mapping approaches (unsupervised, supervised, fuzzy supervised and GIS post-processing). The GIS post-processing approach proposed in their research improved the mapping results, showing the highest overall accuracy of 89.33% as compared to other approaches. The fuzzy supervised approach yielded a better accuracy (87.67%) than the supervised and unsupervised approaches. The fuzzy supervised approach effectively dealt better with the heterogeneous surface features in residential areas. It is likely that a combination of approaches would yield the best classification accuracy. First separating the remote sensed pixels into sets based on a majority-voting rule. Voting is a commonly used technique in random forest classification, which has advantages in that it can yield classifications from a blend of topographic and spectral data sources, particularly if a binary classification is preferred, as in urban/non-urban classifications. For the ground control or Regions of Interest (ROI) required for training the models, Allitt and Tewkesbury (2009) describe a full methodology for obtaining sampling areas for the mapping of urban creep. A complex sampling strategy was developed to sample this data according to drainage system type, soil type, house type, house footprint area, depth of front gardens and perhaps most importantly by socio-demographic factors. Such a procedure ensures selection of representative and diverse examples of urban land use and is particularly important if results are to be used for interpretation of urban creep by development type, age or demographic.

Discussion

This review has identified a growing body of literature attempting to investigate the extent of urban creep in UK urban areas and the hydrological impacts of that. What is clear is that there have been a range of methods employed and that manual and image classification-based methods offer the most robust insights into the scale of urban creep that UK areas are undergoing. Some of the more significant results do not come from peer reviewed sources and are light on details, rendering objective review difficult. For example there are no clear methods in the Royal Horticultural Society (2005) report. Also, given the fine scale that urban creep occurs at, it is not suitable to use proxy methods such as population projection data (Houston et al. 2011). Of those providing detailed estimates, rates of urban creep varied from 0.4m^2 per house per year using a semi-automated method (Newcastle: Allitt and Tewkesbury, 2009) to 6.1m^2 per house per year using a manual change mapping method (Haydon Wick: Haddock et al. 2015).

The values provided by Allitt and Tewkesbury (2009) are the most robust and have been widely used in other studies, with Triolet (2012) taking an average 0.7m^2 per year figure and using this in combination with property numbers, and Ofwat (2011) who used the creep estimates in combination with projected population. They provide values in the range between 0.38m^2 and 1.094m^2 per house per year. If we were to employ the average figure of 0.75m^2 per year this would equate to a decadal increase in impervious area due to urban creep of 7.5m^2 per house per decade – much less than the 59m^2 per house per decade reported for bungalows in Swindon by Haddock et al. (2015). There are no direct assessments using such data as to what urban creep might realistically contribute to urban imperviousness coverage in the future. Certainly, any such assessment would have

to consider changes in urban design and realistic limits on how much creep can physically occur in a developed area.
It is important to note that urban creep is spatially and temporally variable, and is also likely to vary with type, and age, of development, as well as the available green space to expand into – as shown by Haddock et al. (2015). Rates reported from different studies sample different subsets of the UK housing stock and are therefore likely to vary. Realistically, urban creep is not a single figure but a set of figures for different developments, different time periods and different areas of the country. The accuracy of the estimated rates will also be affected by the time of year, accuracy of the method and sample size. The previous studies have had limitations in one or more of these areas; what is required is a transparent, repeatable method and more robust results, derived over a larger spatial area.

It is worth noting that despite there being a 10% uplift in storm water flows to account for urban creep (beyond possible uplifts due to climate change and associated impacts on rainfall uplift) in current urban storm drainage design guidance from the EA in England and Wales (EA, 2013) we were not able to discern from where this figure was derived or if it has any sound quantitative research basis.

This review has shown that only one study has used a detailed semi-automated approach to map urban creep, and that manual and proxy methods have been used more widely. The manual and proxy methods were suitable for the type of smaller scale study attempting to quantify urban creep and assess hydrological impacts in a change-response type framework. They were not sufficiently accurate however, or readily repeatable, for deriving detailed and accurate estimates of urban creep over larger areas. What was shown by Allitt and Tewkesbury (2009) is that given the right fine scale mapping product, in combination with other datasets such as OS MasterMap™, it is feasible to map large areas of urban creep across UK urban areas using a sampling strategy. This suggests that image-classification based methods will be the most cost-effective and repeatable for mapping large areas of urban creep and deriving accurate estimates.

There is a large body of literature and numerous methods and tools available for mapping urban land use change but few have been tested at such a fine scale resolution of change. One of the main issues noted is the impact of green areas that may lead to underestimation of true urban extent at the urban creep scale. Hybrid-object classification methods pose the best possibility of reducing this error and high levels of accuracy have been shown in recent studies by Muhs et al. (2016) and Huang (2016). Similarly there are indications that a combination of other approaches such as unsupervised, supervised, fuzzy supervised and GIS post-processing (Thapa et al., 2009) could yield the best classification accuracy. A suitable approach to testing the right model for application is suggested by Stephens and Diesing (2014), whereby starting with simpler, lightweight models could prove the best approach to balancing accuracy against other constraints.

Finally, it is also important to note that this area is undergoing rapid development. Currently, large organisations like Google, Microsoft and Amazon are investing in, and exploring, methods to apply machine learning methods to automatically analyse, categorise and classify photography. Environmental science can potential benefit from these advances in machine learning. This means that it is likely that our ability to classify aerial photography will improve in the coming years as techniques evolve.

Conclusions

This evidence review has identified that while there is a large body of literature assessing and developing refined methods for mapping urban land use change at the catchment scale there currently exist only limited studies assessing urban creep in the UK and only one primary study by Allit and Tewksbury (2009) undertaking semi-automated mapping of urban creep using remote sensing imagery. This study was undertaken in 2009 and thus there is considerable scope for improving upon the published methods given recent data and software improvements, and considering advancements in methods for mapping urban land use change in the international literature. This wider international evidence base however does not necessarily map the small scale creep that is the focus of this review, and as such requires further consideration.

There has been specific focus on urban creep in Scotland by several studies, but none have provided robust measurement of urban creep rates over a period of time. Wright (2010) and Wright et al (2011) point to large proportion of urban properties having increased areas of impervious hardstanding post construction. Kelly (2016) has quantified rainwater runoff using current and future rainfall intensities with theoretical changes to impervious cover and soil type, and found both changes important drivers of increased runoff volumes. A more detailed analysis is required to understand the rates of urban creep and scope for further creep in the future.

Here we consider the available evidence in light of how to develop and provide methods to map urban creep inScotland considering accuracy, data and software requirements, cost-effectiveness, and reproducibility.

Proposed solution

Based on experience of image classification and knowledge of the literature, the Random Forest classifier (Breiman, 2001) is likely to be the best classification algorithm for mapping urban creep. Since its development in 2003 it has gained popularity as a simple and accurate classification algorithm, and has been shown to outperform traditional algorithms and other machine learning algorithms (Cracknell & Reading, 2014). Therefore we will initially explore Random Forest as a one–stage solution. If the accuracy is poor we will explore the two-stage solution proposed whereby the more easily identified areas, with highest accuracy, are classified and then screened out, enabling a subsequent classification to focus on the harder to identify regions.

Accuracy

Urban creep operates at very small scales, so to detect urban creep between two classified images the mapping accuracy will have to be very high for both images. A classification accuracy of 85% is often taken as a baseline for accurate land cover mapping from satellite-data, although many studies fail to achieve this (Foody, 2002). However, given the small scale of urban creep, which may be a change of less than 1% of the area for a given housing area over a given time, an 85% accuracy is obviously too low. For urban creep levels as low as a 1% change in area the mapping accuracy of the impervious and pervious classes will have to be 99%, or more, to achieve a good change detection accuracy. This is an incredibly high accuracy and is unlikely to be achieved. However, a composite method maybe possible, whereby accurate classifications (but less than a 99% accuracy) are used to determine change, after which the change is manually reviewed to remove any false positives. Care would have to be taken to minimize the occurrences of false omissions i.e. areas of urban creep that were falsely classified as pervious surface in the second classification. For any method validation of the classification against a carefully defined set of validation data that are not used for training the image classifier will be critical to provide confidence in the levels of urban creep reported. The individual classifications will need to be validated, but more importantly the resulting change will need to be validated to show the accuracy of the change detection.

Data and software requirements

There have been considerable advancements in remote sensing imagery and software in recent years, yet little focused application on the scale of urban creep. Given the need to map small scale change that occurs incrementally over long periods of time this limits any assessment of change to using only recent data. As such the only viable option rests upon aerial photography in combination with other ancillary data such as UK MasterMap™. Regarding software, there are a wide range of open source packages available, which provide image classification methods, such as QGIS, R and Python. The QGIS solution is easy to use, but does not provide a probability surface. The probability surface is useful for identifying poorly classified areas. Whereas, the R-based method provides a probability output, but is less user friendly. The Python solution has not yet been assessed by the CEH team. We would thus consider a specific task in developing methods to map urban creep will be to assess possible software and select the most suitable given the available data.

Cost-effectiveness

Although urban mapping is expensive, remote sensing is a more cost-effective technique than alternative methods which might involve more labour intensive approaches such has manual digitisation or field survey. This review has identified the best approach will be to use open source software free of license fees, and where possible public domain spatial data and royalty free aerial survey data. Alterative, non-open source software, where suitable, should also be identified and assessed.

Reproducibility

Providing a reproducible result is an important element of developing any method where data are for applied, rather than research purposes, as the method may have to be applied to different areas, by different individuals, for different times, and provide data for applications such as engineering. This review has identified both manual digitization and semi-automated change mapping from aerial imagery provide reproducible methods, but that semi-automated methods using software offer the most routine and functional means of providing reproducibility in results and lessons subjectivity. We would therefore recommend semi-automated change mapping methods using open software to best ensure reproducibility.

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