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Development and appraisal of long-term adaptation pathways for managing heat-risk in London

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A B S T R A C T

The risk of residential overheating and mortality is increasing due to the effects of global warming and the urban heat island effect and needs to be addressed through climate change adaptation. 'Adaptation pathways' have become widely recognised as an adaptation planning approach, but they have not been utilised for long-term planning for city-scale urban heat risk management. This paper applies adaptation pathway methodology to urban heat risk management. We use spatially coherent downscaled probabilistic climate change projections that account for changes in urban-land cover and the urban heat island to appraise adaptation pathways and inform long-term adaptation planning. We demonstrate that adaptation strategies focusing solely on urban greening or building level adaptation based on current best practice are unlikely to cope with the increasing levels of risk. Air-conditioning may play a growing role in managing heat-risk; however, increasing air-conditioning will exacerbate the urban heat island and further increase the risks of overheating.

1. Introduction

Adapting to increasing mean and maximum temperatures, and heatwaves that are projected to increase in both frequency and severity is a significant challenge for urban authorities globally (Hunt and Watkiss, 2010; IPCC, 2014). Without proportionate adaptation, increasing heat-risk is likely to result in increasing heat-related mortality (Gasparrini et al., 2015; Hajat et al., 2014; Stone et al., 2014; Taylor et al., 2015); additional residential overheating (Porritt et al., 2012; Taylor et al., 2015; ZCH, 2015); reduced infrastructure performance (Jenkins et al., 2014a); and, in extreme cases, it may exceed the threshold for human adaptability and threaten the viability of cities (Pal and Eltahir, 2015).

In addition to climate change, the implementation and effectiveness of urban adaptation strategies will be strongly influenced by socio-economic changes including population, demographic, land-use and technological change (IPCC, 2014). Adaptation pathways have demonstrated significant potential as an adaptation planning approach under such conditions of deep uncertainty (Haasnoot et al., 2012; Siebentritt et al., 2014; Barnett et al., 2014; Rosenzweig and Solecki, 2014; Lawrence et al., 2013; Wise et al., 2014; Haasnoot et al., 2013; Kingsborough et al., 2016). A pathways approach that sequences the implementation of actions over time, to ensure the system adapts to the changing social, environmental and economic conditions, will build flexibility into the overall adaptation strategy (Ranger et al., 2010; Haasnoot et al., 2012).

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The combined effects of the urban heat island (UHI) and climate change are projected to significantly increase summer temperatures and the number of heatwaves[1] in London (McCarthy et al., 2010; Mavrogianni et al., 2011; Murphy et al., 2009). A heatwave equivalent to the 2003 heatwave – which resulted in 650–1000 excess deaths in London (D'Ippoliti et al., 2010) – is projected to have a return period of 1 in 2 years in the 2080s, under a medium emissions scenario at the 50% probability level (Murphy et al., 2009; LCCP, 2012a).

While the risk of mortality due to heat in London remains lower than that due to cold (Gasparrini et al., 2015), heat-risk is expected to increase as the climate warms and extreme heatwave events become more common (Jenkins et al., 2014b; Taylor et al., 2015; Wolf and McGregor, 2013). Heat-risk associated with increased mortality and overheating of people, buildings, infrastructure and urban environments is increasing and needs to be addressed through adaptation (Nickson et al., 2011; LCCP, 2012b,a; Hajat et al., 2014; Jenkins et al., 2014a; Jenkins et al., 2014b; ZCH, 2015; Taylor et al., 2015).

Limited research exists that estimates the vulnerability of populations to heat-risk based on a combination of population and environmental variables at the city scale (Taylor et al., 2015). Wolf and McGregor (2013) used principal components analysis to create a heat vulnerability index for London that accounted for UHI, living in a flat, population density, age, illness, socio-economic status, social isolation, and ethnic minority status. They found spatial clustering of areas of high heat vulnerability in Central and East London that coincide with areas of potentially high heat exposure. Taylor et al. (2015) examined the risk of mortality in London during hot weather events by combining data on population age and distribution, UHI, and dwelling characteristics to calculate the spatial variation in heat-related mortality risk across London. Spatial variation of heat-related mortality was found to reflect background mortality rates due to population age, while dwelling characteristics were found to cause a larger variation in risk than the UHI. This research, however, did not consider future climate, socio-demographic or adaptation scenarios.

Jenkins et al. (2014b) utilised high spatial resolution probabilistic projections of urban temperatures with projections of demographic change as part of a risk assessment at the ward scale in London. They found that reducing indoor temperatures by 1–2 °C reduced both annual heat-related mortality and residential overheating compared to no-adaptation in future scenarios, however limited consideration was given to the nature and feasibility of potential adaptation actions.

A range of actions including land-use planning, building design, community resilience, and emergency planning and response must be considered together for cities to manage long term heat-risk. Research on the effectiveness of localised adaptation actions in London is growing, including solar shading; building insulation and ventilation (Porritt et al., 2012); roof insulation and window upgrades (Mavrogianni et al., 2012); green roofs (Virk et al., 2015, 2014); and occupant behaviour (Mavrogianni et al., 2014). However, evidence on the effectiveness of adaptation actions in lowering heat-related mortality is limited (Frontier Economics, 2013), and quantifying the effectiveness of specific adaptation options into an associated temperature based increase in resilience at the city scale remains a significant challenge (Jenkins et al., 2014b). There is limited research on existing and future heat-risk that actively considers the effectiveness of specific adaptation actions in managing that risk through time at the city scale (Stone et al., 2014).

There is a need to continue developing, trialling, critiquing and demonstrating how pathways approaches can be utilised in informing and motivating adaptation planning (Wise et al., 2014; Haasnoot et al., 2012; Barnett et al., 2015; Kingsborough et al., 2016).

Adaptation pathways have not been applied to long-term planning for urban heat-risk at the city scale, and a lack of demonstration in this context limits decision-makers' confidence in their utility. This paper explores the potential for adaptation strategies to manage future heat risk under a long-term population growth and climate change scenarios.

This research adopts a framework for adaptation planning and the development of adaptation pathways developed by Kingsborough et al. (2016); generates quantified estimates for the effectiveness of a range of adaptation options; and utilises an updated probabilistic spatial heat-risk assessment model developed by Jenkins et al. (2014b) to demonstrate how adaptation pathways in response may manage long-term heat-risk in London. We present a quantified assessment of how heat-risk in London is projected to vary depending on the choice of adaptation pathway under a medium greenhouse gas emissions and population scenario. This research focuses on Greater London: assessing mortality risk, thermal discomfort in residential buildings, and adaptation pathways.

2. Methodology

The adaptation planning framework developed by Kingsborough et al. (2016) is a risk -based and iterative approach that prioritises management of existing risks, and guides the development of long-term adaptation pathways. Within our adaptation planning framework (Fig. 1), the key steps in the development of adaptation pathways include: a review of the potential usefulness of adaptation pathways; the identification of an adaptation canvas; selection of adaptation portfolios; the development of adaptation pathways; and an appraisal and visualisation of adaptation pathways. This section outlines their application to the development of adaptation pathways for heat-risk.

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[1] Two heatwave definitions are commonly used in London: Public Health England define a heatwave (Level 3) as two consecutive days above 32 °C with an overnight minimum above 18 °C (2015), while the London Resilience Partnership define it as five days above 32 °C with overnight minimums above 15 degrees (2014).

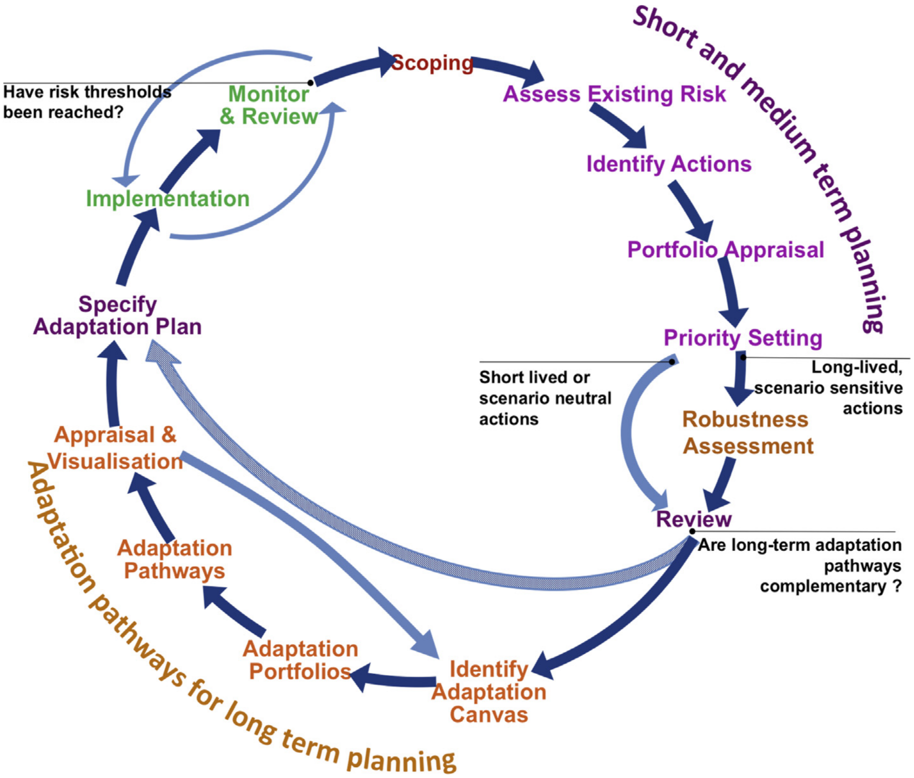

Fig. 1. Integrated adaptation planning framework (Kingsborough et al., 2016).

2.1. Review

A policy and document review of risk management, governance and planning approaches in London was undertaken, including the Mayor's Climate Change Adaptation Strategy (GLA, 2011), the London Plan (GLA, 2015b), the London Infrastructure Plan (Mayor of London, 2015) and the Heatwave Plan for England (PHE, 2015), to better understand the extent existing and future heat-risk is considered; identify relevant planning horizons; establish decision criteria and risk thresholds; and understand stakeholder perspectives on the potential value in developing long-term pathways.

Semi-structured interviews were also conducted with stakeholders from the Greater London Authority (GLA) and the Environment Agency London Team to identify near and long-term priorities, ways in which they may or may not be affected by climate change, and perceived barriers and enablers in adapting to changing heat-risk. Multiple meetings of the London Climate Change Partnership (a collection of organisations that contribute to increasing London's climate change preparedness) and the London Working Group on Heat-risk (a collection of organisations that share their experiences working to address heat-risk) were attended in 2013–2015 to further understand the context for adaptation planning in London. The review phase assisted in identifying which actions would be included in the subsequent portfolios and pathways.

2.2. Adaptation canvas

An adaptation canvas provides an opportunity to consider a wide range of adaptation actions, their possible limits and associated uncertainties in a visual manner that illustrates the potential solution space.

Fig. 2 is a stylised causal loop diagram that identifies potential urban heat actions, the relationships between the actions and the nature of the impact of each action on mortality and residential discomfort. The actions are grouped according to the spatial scale at which they are most applicable. This paper focuses on three categories of adaptation action – urban greening, air-conditioning, and upgrading the building stock – as not all of the identified adaption actions could be considered within the scope of this research. The selected actions were identified as potentially having a long-term impact on the heat-risk level at the city scale; interesting to stakeholders; and quantifiable. As we completed a quantitative appraisal of the adaptation pathways, the methodological steps to develop plausible estimates of the effectiveness of selected adaptation actions and their implementation potential are also described below.

Early warning, emergency response, communication and stakeholder engagement actions (PHE, 2015; Matthies and Menne, 2009; Hajat et al., 2010; Wolf and McGregor, 2013), and the supporting institutional structures and capacities (Zaidi and Pelling, 2015) play a valuable role in managing the impacts of heat-risk on individuals and communities. However,

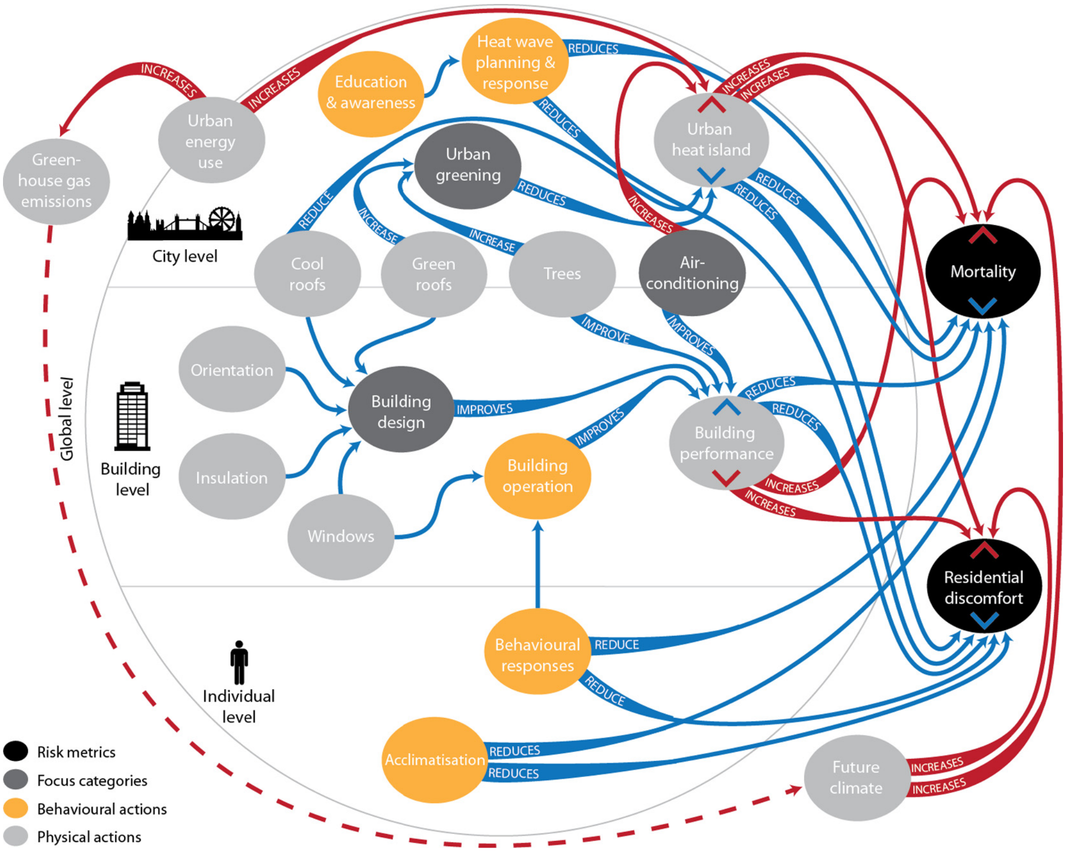

Fig. 2. Urban adaptation actions and their impact on heat-risk.

due to the dearth of reliable data on the costs and effectiveness of heatwave response planning (Frontier Economics, 2013) and research on the effect of behavioural adaptation on vulnerability (Zaidi and Pelling, 2015) these actions are not appraised further in this research, whilst it is acknowledged they will form an important component of future adaptation portfolios.

2.2.1. Urban greening

Observational and modelling studies have found vegetative cover and high-albedo materials to be associated with lower surface and near-surface air temperatures than sparsely vegetated areas with low albedo (Stone et al., 2014; Hart and Sailor, 2009; Virk et al., 2014; Li et al., 2014). The shading and evapotranspiration provided by trees and green spaces may reduce air temperatures and surface temperatures by 2–8 °C in cities (ARUP, 2014). Green space accounts for 47% of Greater London (GiGL, 2014) and current levels of greening are estimated to reduce night temperatures by 2–3 °C (Mavrogianni, 2014). Reducing Central London's 598 km^2 vegetated region by 152 km^2 is estimated to increase average annual temperatures by 0.5 °C, while increasing vegetation in London by 50% is estimated to decrease the average night time UHI by 0.6 °C (McCarthy et al., 2010).

We identified existing land-cover characteristics using spatial analysis of existing land-use categories in London from classifications in the MasterMap database (OS, 2015b), existing green space provisions in London from the GiGL land-type database (GiGL, 2014), and the GLA green roof database (GLA, 2014b). Following this analysis we developed five scenarios of urban greening to facilitate the exploration of a wide range of futures, as detailed in Table 1.

We used Equation 1 developed by McCarthy et al. (2012) to estimate the impact of land-use change on temperatures in London. Change factors derived using Eq. (1) were calculated for Central London, for the five urban greening scenarios. The change factors were applied across Greater London by combining them with projections from a spatial weather generator (WG) (described in Section 2.5.1) to explore the cumulative impact of urbanisation and climate change. This approach has not previously been applied to a planning study or in the appraisal of adaptation actions.

$$\Delta T = B_1\chi + B_2\chi^2 \qquad (1)$$

χ = total urban land cover (in 100 s of km^2)
ΔT = temperature change (°C)
Coefficients B_1 and B_2 are specified in McCarthy et al. (2010).

Table 1
Urban greening scenarios.

Scenario	Description
25% increase in vegetation cover	Vegetated garden areas increase 30% (multi-use land-type), greening of 50% of roofs and 25% of roadside areas, and no loss of existing green space
25% decrease in vegetation cover	Paving of 15% of London's existing natural areas and 50% of all backyards
Green roof saturation	The maximum estimated potential for green roof installation is 82% of the total roof area within the Victoria Business Improvement District (Rogers et al., 2012): an equivalent of 180 km^2 in Greater London
50% increase in vegetation cover	Greening 82% of roofs, 75% of roadside areas and 70% increase in vegetated gardens (multi-use land-type)
50% decrease in vegetation cover	Paving of 60% of London's existing natural areas and 75% of all existing backyard vegetation

2.2.2. Air-conditioning

Residential air-conditioning is a response to increasing summer temperatures or the occurrence of heatwaves, but its purchase is also typically influenced by economic and cultural factors (Sailor and Pavlova, 2003; Davis and Gertler, 2015). In the US, market saturation has increased from 2% in 1955 to now exceeding 90% (Sailor and Pavlova, 2003; EIA, 2011). We project air-conditioning uptake in response to increasing temperatures as well as exploring high uptake scenarios driven by cultural and economic change.

Whilst air-conditioning can deliver significant localised benefits in terms of reducing residential overheating, it is not a preferred adaptation action in London (GLA, 2011) as the waste heat contributes to the UHI (Davies et al., 2008; Mavrogianni et al., 2011; McCarthy et al., 2012); it increases energy demand and greenhouse gas emissions (Day et al., 2009); and it is likely to be a costly and inequitable cooling solution (ASC, 2011). Heat released from energy use in present day London is estimated to account for approximately 15% of the average summer night time UHI of 2 °C and 42% of the winter UHI of 1.2 °C (McCarthy et al., 2012).

Air-conditioning is uncommon in London – an estimated 1–3% of households use fixed or portable air-conditioning units (Day and Opara, 2012; BRE, 2013) – but uptake is potentially rising, with one survey finding 6% of Londoners have installed air-conditioning (ComRes, 2015). Given the current low levels of uptake and the projected change in climate there may be significant future increases in air-conditioning uptake. Fig. 3 outlines our method to estimate the uptake of air-conditioning and the resultant impact on the UHI. We calculated the impact of waste heat emissions on the UHI for (i) scenarios of air-conditioning uptake driven by increasing temperatures under a medium emissions climate change projection (including feedbacks between the UHI and air-conditioning usage); and (ii) 50% and 100% air-conditioning uptake scenarios.

We used McNeil and Letschert's (2010) updated version of Sailor and Pavlova's (2003) relationship between cooling degree days (CDD) and air-conditioning market saturation for 39 US cities to estimate a market saturation (S) level for air-conditioning in London, as per Eq. (2).

$$S = 1.0 - 0.949\exp(-0.00187 \times CDD) \tag{2}$$

These regressions provided an initial estimate of potential air-conditioning uptake. This method has been used in a number of studies, including Riviere (2009) national-level estimates for air-conditioning in Europe.

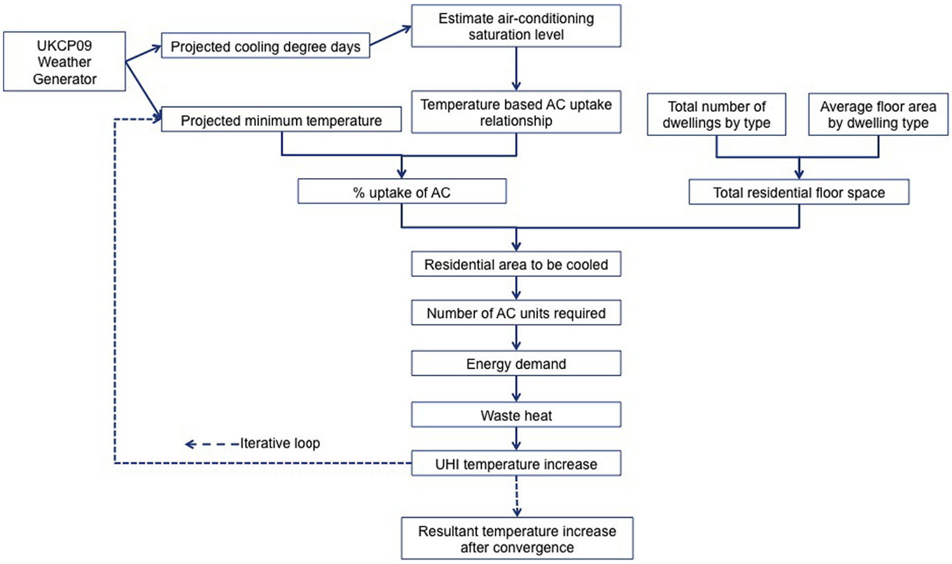

Fig. 3. Method to estimate the impact of air-conditioning on the UHI.

CDDs with a base temperature of 18 °C (reflecting minimum temperature (Tmin) values used within heatwave definitions in London) were calculated using the UKCP09 WG and threshold detector (Murphy et al., 2009). In the 2080s high emission scenario the mean annual number of CDDs is 550 with an air-conditioning saturation level of 66%, this corresponds to an average summer Tmin of 17 °C.

From this analysis a logistic growth model for air-conditioning, based on projected increases in summer Tmin, was created as per Eq. (3).

$$Uptake\ of\ air\ conditioning = \frac{1}{1 + e^{-(t-\mu)/\sigma}} \tag{3}$$

t = average summer Tmin
μ = temperature at which the rate of air-conditioning uptake peaks
σ = standard deviation of distribution

The values of μ and σ were chosen to produce an idealised growth pattern for air-conditioning uptake that corresponds to an existing level of air-conditioning of approximately 1% for an average summer Tmin of 12 °C (as per UKCP09 baseline period), and maximum uptake when the average summer Tmin is 17 °C (as per UKCP09 2080s high emission scenario). From this relationship for a given mean summer Tmin we estimated the percentage of London's residential floor space that will be air-conditioned and the corresponding energy demand. We then used Eq. (1) (McCarthy et al., 2012), with χ = level of heat emissions in GW, to estimate the feedback from energy use on London's UHI.

The method outlined above facilitates a more considered analysis of the relationship between temperature and air-conditioning uptake in the context of a changing climate and London's UHI: as temperatures rise the uptake of air-conditioning will likely increase, which will in-turn increase energy use during summer and exacerbate the UHI. For a given level of air-conditioning uptake we estimated the UHI increase, the subsequent additional air-conditioning uptake, and iterated until a stable level of air-conditioning uptake was established. The impacts of varying air-conditioning access for the least and most vulnerable residents in London were explored through scenarios.

2.2.3. Upgraded building stock

Built form, the level of building fabric retrofit, orientation, and the availability and performance of ventilation and other building characteristics may influence the risk of buildings overheating (Mavrogianni et al., 2012). While occupant behaviour (Mavrogianni et al., 2014) and external climate (Oikonomou et al., 2012; Taylor et al., 2015) can influence the relative overheating risk within building types. The effects of built form and dwelling characteristics appear to have a greater influence on variation in internal temperatures than the location within the UHI (Oikonomou et al., 2012; Taylor et al., 2015). A number of adaptation actions may be implemented to reduce the overheating risk within London's buildings (Taylor et al., 2015; Porritt et al., 2012). Previous research has indicated that during a typical hot period in London, roof insulation and window upgrades decreased peak internal temperatures by 1.3 °C (Mavrogianni et al., 2012).

Taylor et al. (2015) undertook thermal performance simulations for 17 London building archetypes across 8 orientations using EnergyPlus (US-DOE, 2013) at an hourly time-step, using weather files for a Central London design summer year. We further analysed these simulation outputs to estimate the effectiveness of improving the overheating performance of the eight most common building types in London. The difference between external and internal temperatures for each hour when the external temperature was above 24.8 °C was calculated. A mean building performance factor (MBF) was calculated for each of the 2016 simulations. Cumulative distribution functions of the MBFs were plotted for each of the eight building types: the minimum, mean and maximum values are shown in Table 2.

Future research is planned to update the building physics models to explicitly include a range of specific adaptation actions (Taylor et al., 2015). For this research however, we considered building level adaptation to mean each building could be renovated or replaced such that its overheating performance would be equivalent to the best performer in its type. We considered a scenario of natural replacement, but because the replacement of UK building stock is low (typically 1% per year) only around 20% of buildings will be replaced between now and the 2050s (ASC, 2015; GLA, 2015a). In addition we considered renovation scenarios in which 50% and 100% of buildings are upgraded.

Table 2
MBFs for eight London building types (°C).

	Minimum MBF	Mean MBF	Maximum MBF
Bungalow	0.55	1.74	3.13
Converted flat	−1.57	0.86	4.03
Detached	−2.02	−1.12	−0.19
End terrace	−1.23	0.38	3.02
High-rise purpose-built flats	−4.75	−2.14	7.75
Low-rise purpose-built flats	−2.96	−0.58	3.48
Mid-terrace	−1.78	−0.18	2.48
Semi-Detached	−1.78	−0.31	1.67

2.3. Adaptation portfolios

Adopting a portfolio approach provides the flexibility to cope with various possible future conditions and can help compensate for the inevitable weaknesses or vulnerabilities of any one action. Portfolios are drawn from the adaptation canvas and may be selected: in consultation with stakeholders; within a modelling environment to respond to threshold levels of climate-risk; through expert judgement; or a combination thereof (Haasnoot et al., 2013). Portfolios should be of interest to stakeholders and include adaptive actions that may be appropriate under a range of potential futures. Due to the exploratory nature of this research we specified 12 portfolios using a combination of urban greening, air-conditioning and building level adaptation actions. These portfolios were intended as informative scenarios for long-term decision-making.

2.4. Adaptation pathways

Pathways may also be scheduled through stakeholder consultation, expert judgement or within a modelling environment to respond to threshold levels of climate-risk (Haasnoot et al., 2013; Reeder and Ranger, 2011). Pathways were selected to represent a range of adaptive strategies that may be informative to stakeholders in London. The actions in the portfolios were scheduled to explore feasible timescales over which adaptation options could be implemented. Each pathway is a scenario used to inform a planning process, as opposed to being a proposed plan. For the purposes of this research one pathway was developed for each portfolio as described in Table 3. The values in Table 3 reflect the scenario results for urban greening, air-conditioning, and upgraded building stock generated following the methods outlined above.

2.5. Pathway appraisal

The appraisal of sequential adaptation pathways demonstrates to decision-makers how climate-risk may (or may not) be managed. We used an urban climate change impact assessment model, which built on the impact assessment framework described in Jenkins et al. (2014b), to appraise the effectiveness of adaptation pathways in managing heat-risk.

2.5.1. Modelling framework

The model incorporates probabilistic projections of daily maximum (Tmax) and minimum (Tmin) temperatures, at a 5 km^2 resolution, from a spatial version of the UKCP09 WG (Kilsby et al., 2011). This enables a probabilistic analysis of heat events, as well as providing an assessment of underlying climate model uncertainties (Jenkins et al., 2014b). The WG is conditioned upon a large ensemble of future climate conditions obtained from the UKCP09 climate projections (Murphy et al., 2009). Daily time-series data for 30-year stationary sequences are taken from the WG for each grid cell in the research area. These series are generated 100 times each, with each run based on a different randomly sampled vector of change factors, to allow probabilistic analysis. Data was generated for a baseline period of 1960–1990 and then for three 30-year time periods centred on the 2030s, 2050s and 2080s. The pathway appraisal was undertaken using the UKCP09 medium emissions scenario, this corresponds to the A1B Special Report on Emissions Scenario (SRES) (Murphy et al., 2009). The SRES A1B is equivalent to a median global mean temperature increase of approximately 2.75 °C by the 2080–2100 period (compared with a 1980–1999 baseline); it is positioned between Representative Concentration Pathways 6.0 and 8.5 (IPCC, 2013).

A population projection based on long-term growth trends and the 2011 census was used to 2040 (GLA, 2014a). From 2040–2100 long-term baseline projections (Zuo et al., 2014), scaled to account for the greater than projected growth in London between the 2003 and 2011 censuses, were used. This represents a population increase from 8.6 million in 2015 to 10.0 million in the 2030s, 10.9 million in the 2050s and 11.0 million in the 2080s. For each London borough,[2] the data was disaggregated to a ward scale based on the present day population distribution.

Housing stock in London grew less than 1% annually in the 2000s, far slower than population over the same period (GLA, 2015a). Given London's relatively slow turnover of building stock, the proportion of property types was assumed to remain constant in this analysis. Estimates of the number of residents living in each of the eight most common building types in London, in each ward, were made based on census data (ONS, 2013), with further dwelling data derived from the AddressBase Plus database (OS, 2015a) and the UKBuildings database (GG, 2013).

Climate hazard was assessed in terms of the exceedance of temperature thresholds. Adaptation actions were integrated into the risk assessment framework, their inclusion modifying the probability that relevant thresholds may be exceeded. For example, urban greening and waste heat from air-conditioning modify the UHI, air-conditioning affects the number of individuals exposed to overheating, and building-level adaptations alter the relationship between internal and external Tmax.

2.5.2. Risk metrics

Heat-risk metrics should provide evidence as to the changing nature of heat-risk, to monitor climate impacts and prioritise adaptation actions. Multiple metrics will be required to understand heat-risk in complex urban systems. Metrics that reflect changes in multiple drivers of risk – including climate change, the UHI, social vulnerability and adaptation action

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[2] There are 32 boroughs, in addition to the City of London, in Greater London, each of which is equivalent to a local government district; which are divided into 628 wards.

Table 3
Scheduling of actions within adaptation pathways.

Pathway	Description	Portfolio	Percentage change			
			Baseline	2030s	2050s	2080s
1	Urban greening – green roof saturation	Increase green roof area	0	41	82	82
		Building upgrade	–	–		–
		Increase green space area	–	–	–	–
		Residential air-conditioning	–	–	–	–
2	Urban greening – 25% increase in green space	Increase green roofs area	0	25	50	50
		Building upgrade	–	–	–	–
		Increase green space area	0	13	25	25
		Residential air-conditioning	–	–	–	–
3	Greening – 50% increase in green space	Increase green roof area	0	45	82	–
		Building upgrade	–	–	–	–
		Increase green space area	0	4	35	50
		Residential air-conditioning	–	–	–	–
4	Air conditioning – temperature driven uptake (random distribution)	Increase green roof area	–	–	–	–
		Building upgrade	–	–	–	–
		Increase green space area	–	–	–	–
		Residential air-conditioning	3	18	40	62
5	Air conditioning – 50% uptake (most vulnerable prioritised)	Increase green roof area	–	–	–	–
		Building upgrade	–	–	–	–
		Increase green space area	–	–	–	–
		Residential air-conditioning	3	9	36	50
6	Air conditioning – 100% uptake (random distribution)	Increase green roof area	–	–	–	–
		Building upgrade	–	–	–	–
		Increase green space area	–	–	–	–
		Residential air-conditioning	3	15	67	100
7	Building stock upgrades – replacement rates	Increase green roof area	–	–	–	–
		Building upgrade	0	12	23	40
		Increase green space area	–	–	–	–
		Residential air-conditioning	–	–	–	–
8	Building upgrade – 50% stock	Increase green roof area	–	–	–	–
		Building upgrade	0	25	50	50
		Increase green space area	–	–	–	–
		Residential air-conditioning	–	–	–	–
9	Building upgrade – 100% stock	Increase green roof area	–	–	–	–
		Building upgrade	0	15	67	100
		Increase green space area	–	–	–	–
		Residential air-conditioning	–	–	–	–
10	Greening & Building	Increase green roof area	0	25	50	50
		Building upgrade	0	25	50	50
		Increase green space area	0	13	25	25
		Residential air-conditioning	–	–	–	–
11	Greening & Building	Increase green roof area	0	7	63	82
		Building upgrade	0	15	67	100
		Increase green space area	0	4	35	50
		Residential air-conditioning	–	–	–	–
12	Air-conditioning, Urbanisation (least vulnerable install air-conditioning)	Increase green roof area	–	–	–	–
		Building upgrade	–	–	–	–
		Increase green space area	0	−5	−16	−25
		Residential air-conditioning	3	9	36	50

– are more valuable to decision makers than those that only reflect the changing climate hazard. We adopted mortality, residential overheating and risk of exceeding target frequency for residential overheating events for this research.

It is well established that high temperatures are associated with increased mortality (Vardoulakis et al., 2014; Hajat et al., 2014; Armstrong et al., 2011; Gasparrini et al., 2015), and mortality has been used as a metric in a number of heat-risk studies (Taylor et al., 2015; Stone et al., 2014; Jenkins et al., 2014b). Mortality is of interest to a broad range of decision makers, but especially those in the health sector (Zaidi and Pelling, 2015).

The baseline background daily mortality rate was identified from data on annual mortality rates at the ward level (Zuo et al., 2014), and summer weighted daily mortality rates for each future time period were updated from Jenkins et al. (2014b). Heat-related mortality was calculated based on epidemiological relationships between mortality and temperature: a mean daily temperature threshold of 20 °C above which heat-related mortality increases on average by 3.1% per 1 °C rise was adopted (Jenkins et al., 2014b). Annual average heat-related mortality was calculated for each ward and across Greater London.

It should be noted that, as mortality estimates are based on historic data, it remains to be seen whether these relationships will hold for the future given potential acclimatisation as well as infrastructure, technological and institutional governance changes (Zaidi and Pelling, 2015; Armstrong et al., 2011). Given the importance of mortality estimates to public health management, it is a useful metric to use in adaptation planning, however it should be used with an understanding of its limitations, and as part of a portfolio of indicators.

The level of residential overheating is an important and useful metric for heat-risk as indoor temperature extremes are of more direct consequence to heat vulnerability than the occurrence of climate based heatwaves, and are mediated by individual building use and design (Zaidi and Pelling, 2015; Mavrogianni et al., 2012; Mavrogianni et al., 2014).

There is currently no universal definition of residential overheating. An adaptive comfort based approach (CIBSE, 2013) that seeks to account for acclimatisation has been developed for the UK (ZCH, 2015). However, the most commonly adopted overheating criteria are based on CIBSE's Guide A (2006), which specifies that above an internal temperature of 28 °C people will feel discomfort in living spaces. Based on this internal temperature threshold, in combination with the building performance factors described in Section 2.2.3, we identified building specific external temperature thresholds above which residential discomfort may occur in each building type, as per Table 4.

Whilst this approach simplifies the processes that relate external to internal temperatures at an individual building level, they do provide an indication of the overheating risks related to different residential building types and how such risks could change in the future (Jenkins et al., 2014b).

We estimated the number of people subject to residential overheating based on the daily Tmax of the spatial WG simulation in each ward, the number of people living in each building type, and relevant temperature thresholds for each building type. We then calculated the percentage of total residents at risk from thermal discomfort per daily event, as an indicator of the scale of overheating risk.

Heatwave definitions range from those based on the characteristics of a climate hazard, as adopted in London, to those based on the level of impact (Zaidi and Pelling, 2015), such as mortality or economic losses. We propose that as the level of sophistication with which heat-risk is managed increases, similar to what has occurred for other natural hazards such as flooding (Beven and Hall, 2014) and drought (Hall et al., 2012; Brown et al., 2015), there is an emerging role for probabilistic impact-based heatwave definitions. As a demonstration we proposed three potential heatwave levels based on increasing numbers of people exposed to residential overheating, described in Table 5.

Within the impact assessment model, the number of people in each ward exposed to residential overheating each day was calculated across eight building types. A threshold detector was applied to identify when the percentage of residents exposed to overheating in each ward exceeded the heatwave threshold level. Then the number of consecutive days that the threshold level is exceeded is calculated to identify the number of five-day heatwaves. The annual frequency of level 1–3 heatwave events was calculated based on a 30-year model run and the p10, p50 and p90 values estimated based on 100 model runs.

3. Results

The spatial coherence of the WG and impact assessment approach allows data to be aggregated across London for each daily heat event and assessed in probabilistic terms. Results are first presented for individual adaptation categories (Section 3.1) and then in combination as part of our adaptation pathways (Section 3.2).

Table 4
MBFs for eight London building types.

Building type	Existing average external Tmax threshold	Adapted average external Tmax threshold
Converted flat	27.1 °C	27.7 °C
Detached	29.1 °C	29.6 °C
Bungalow	26.3 °C	26.7 °C
High-rise purpose-built flats	30.1 °C	30.9 °C
Low-rise purpose-built flats	28.3 °C	28.8 °C
Semi-Detached	28.3 °C	28.8 °C
End terrace	27.6 °C	28.1 °C
Mid-terrace	28.2 °C	28.8 °C

Table 5
Residential overheating heatwave levels.

Heatwave level	Threshold level Percentage of residents experiencing overheating	Heatwave length Consecutive Days
1	10	5
2	25	5
3	50	5

The results are based on the analysis of 100 model runs, with each run based on a different randomly sampled vector of change factors from the WG. Unless specified otherwise, the results presented are for the median values (50th percentile) under the UKCP09 medium greenhouse gas emissions scenario. Where uncertainty bounds are included in figures the lower and upper bounds correspond to the 10th and 90th percentiles across 100 model runs. Emission scenario uncertainty and socio-economic uncertainties are not represented in the results.

In the 2080s there are estimated to be more than 950 additional heat-related deaths attributed to increasing temperatures and the number of residents exposed to residential overheating is estimated to increase from 18% to 92%. The probability that more than 25% of London's residents will be exposed to 5 consecutive days of overheating is estimated to increase from less than 0.1 in the baseline to more than 2.5 by the 2080s, as per Fig. 4. This highlights the need to consider a broad range of future adaptation actions, portfolios and pathways for city-scale scale urban adaptation in London. Our results show the effectiveness of individual adaptation actions and present the appraisal of our demonstration adaptation pathways.

3.1. Adaptation action appraisal

3.1.1. Urban greening

City-scale urban greening has the potential to decrease the UHI impact, as Table 6 shows, increasing London's urban green space by 50% is projected to reduce future summer Tmax by 0.28 °C. In the 2080s this corresponds to 49 less heat-related deaths each year compared to a no-adaptation scenario, as per Fig. 5. Alternatively, decreasing London's green space by 25% by the 2080s is projected to increase summer Tmax by 0.17 °C, which corresponds to 26 more heat-related deaths

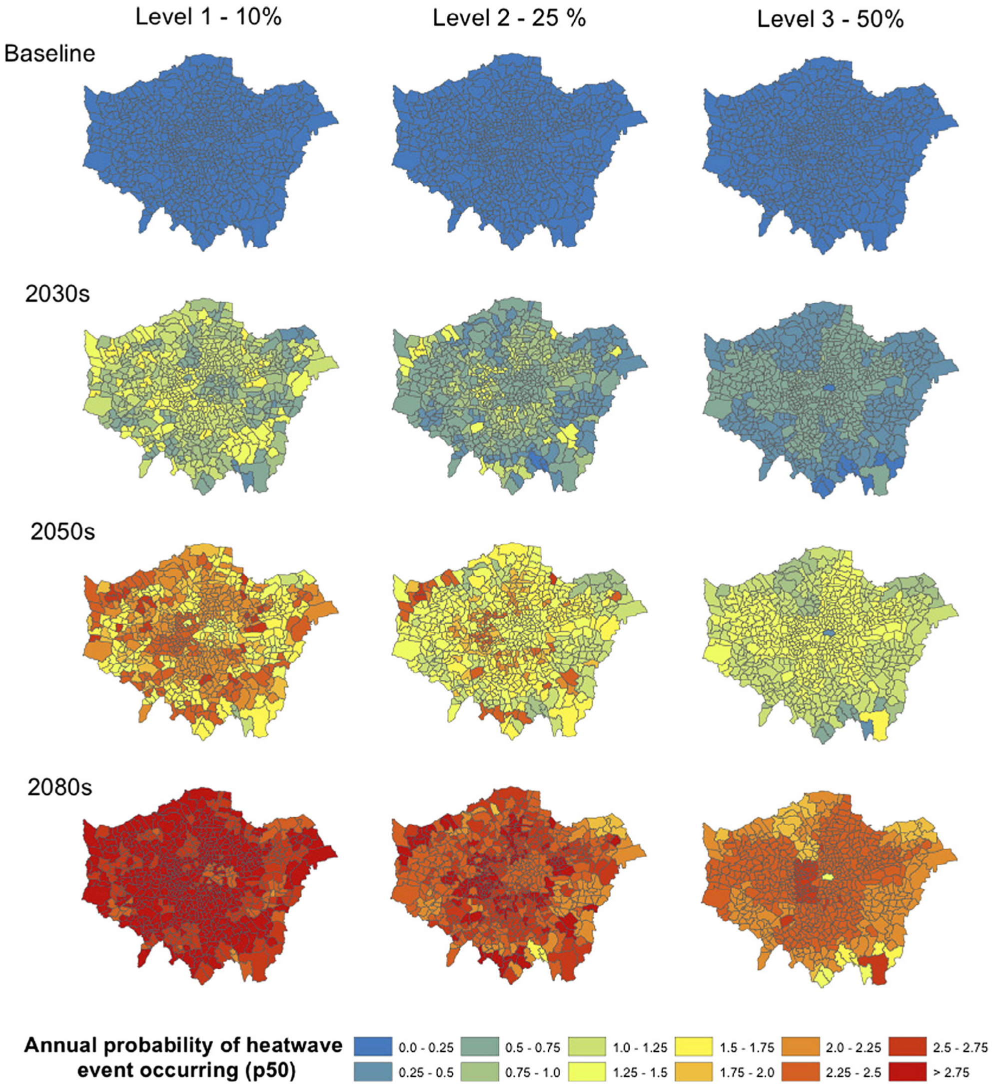

Fig. 4. Level 1–3 residential overheating risk: no-adaptation.

Table 6
Impact of changes in vegetation cover on summer Tmax and Tmin.

Green space type	Existing estimated area	Scenario	Scenario estimated area	Change in summer Tmin	Change in summer Tmax
Green roofs	<5 km^2	Estimated green roof saturation	83 km^2	−0.016 °C	−0.068 °C
Parks/gardens	760 km^2	25% increase in urban green space	950 km^2	−0.038 °C	−0.149 °C
Parks/gardens	760 km^2	25% decrease in urban green space	570 km^2	0.037 °C	0.172 °C
Parks/gardens	760 km^2	50% increase in urban green space	950 km^2	−0.077 °C	−0.275 °C
Parks/gardens	760 km^2	50% decrease in urban green space	1140 km^2	0.073 °C	0.368 °C

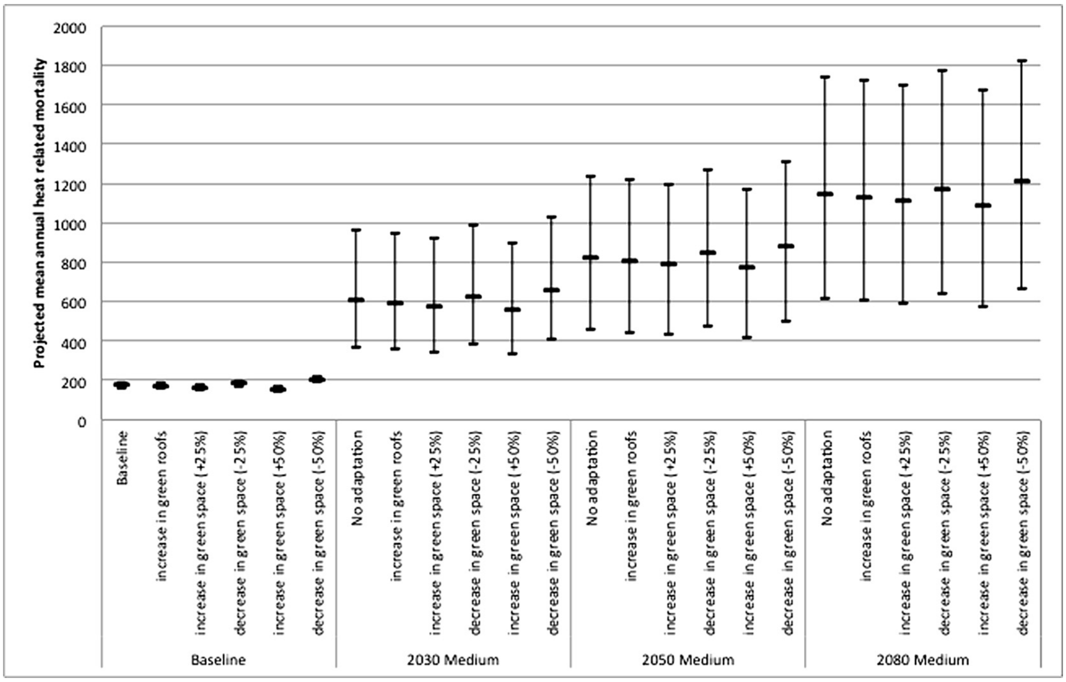

Fig. 5. Estimated annual heat-related mortalities for urban greening scenarios (p10 and p90 are lower and upper bounds).

per year compared to a scenario where existing levels of urban greening are maintained. The difference between increasing and decreasing levels of urban greening by 25% is estimated to be 54 deaths annually in the 2050s and 60 in the 2080s. When considering the number of heatwaves (Levels1–3) and the potential impact of increased greening, we observe heat-risk increasing as green space decreases, as per Fig. 6.

It is noted that these results focus on the impacts of green infrastructure on the UHI and do not reflect localised benefits such as shading of buildings (Rogers et al., 2012; Doick and Hutchings, 2013), or the enhanced insulation provided by green roofs (Virk et al., 2014). Nor do they seek to quantify benefits of urban greening such as storm water attenuation (Stovin et al., 2012) or improved amenity and biodiversity value (Gill et al., 2007; Demuzere et al., 2014).

3.1.2. Air-conditioning

Our estimate of the total energy demand for London assumes that a cooling unit with an energy demand of 1.7 kW (at 30 °C) is used to cool an average size room in London (DCLG, 2014). In a scenario where 100% of the 3.4 million residential dwellings in London (ONS, 2013) were cooled, an additional 13.2GW of peak demand would be generated. Day and Opara (2012) estimated this demand to be 11.5GW, given this result is within 20%, it is considered a reasonable estimate. Differences may be attributed to different methods or assumptions regarding the future mix of cooling technologies, energy efficiency ratios and potential growth in residential floor space.

Table 7 describes the estimated uptake rates for air-conditioning in response to increasing temperatures due to climate change. Whilst London's current uptake rates for residential air-conditioning are low, the results highlight that if uptake is driven in a similar manner to US cities, then under a medium emissions climate change scenario 40% of London's residential floor space may be air-conditioned by the 2050s, increasing to more than 60% by the 2080s. Such a scenario would have significant implications for mortality and residential overheating, especially from an equity perspective as those who are most

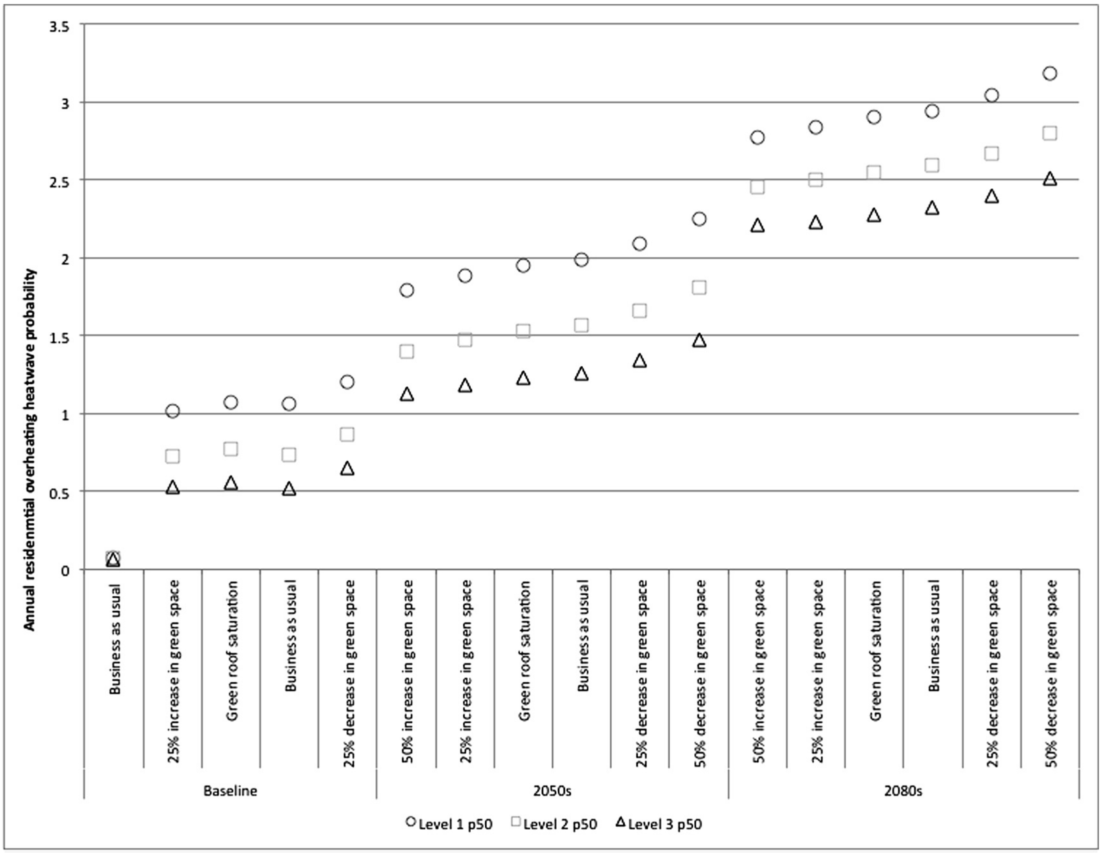

Fig. 6. Median values for London's average annual frequency of Level 1–3 heatwaves.

Table 7
Projected air-conditioning uptake and UHI temperature increase.

Climate scenario		UKCP09 P50 Tmin	London air-conditioner saturation	UHI change in summer Tmin	UHI change in summer Tmax
Time	Emissions	ΔTmin – JJA	Percentage of residents	ΔTmin – JJA	ΔTmax – JJA
Baseline	N/A	0.0	0.7	0.01	0.00
2030	Medium	2.0	18	0.18	0.04
2050	Medium	2.7	40	0.23	0.08
2080	Medium	3.9	62	0.25	0.13

vulnerable to an increasing UHI are often of low economic status (Wolf and McGregor, 2013) and are likely to be least able to afford residential air-conditioning. It would also have significant implications for London's energy generation and greenhouse-gas emissions (Day et al., 2009).

In a scenario where 50% of Londoners utilise air-conditioning summer Tmax and Tmin, are estimated to increase by 0.11 °C and 0.25 °C respectively due to the waste heat's impact on the UHI. As an upper bound under this scenario, if the residents who utilise air-conditioning are the least vulnerable to heat-risk (these are typically healthy and wealthy individuals (Wolf and McGregor, 2013)), it is estimated that there will be 55 additional heat-related deaths per year in the 2080 s compared to a scenario with no change to the UHI, as per Fig. 7.

In London in the 2050 s the median value for the average annual probability that 25% of residents will experience 5 consecutive days of residential overheating is 1.6 assuming there is no adaptation. If it is assumed that the least vulnerable 50% of London's residents install air-conditioning it increases to 2.8 due to the impact of air-conditioning on the UHI, which will affect the most vulnerable residents. However, if the most vulnerable 50% of the population have access to residential air-conditioning it decreases to 1.3, due to the internal cooling provided by air-conditioning. Levels of residential overheating risk at the ward scale, under these three scenarios, are mapped in Fig. 8.

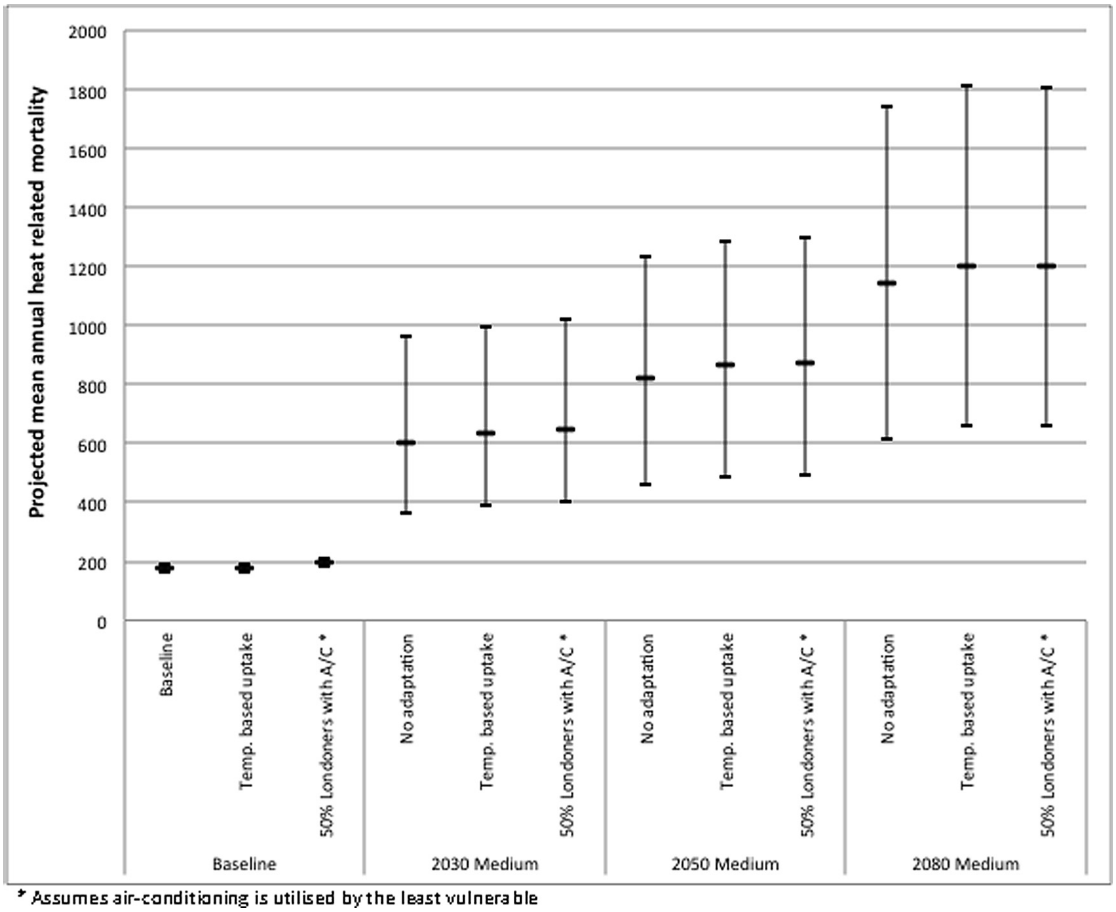

Fig. 7. Mean annual heat-related mortality for residential air-conditioning scenarios (p10 and p90 are lower and upper bounds).

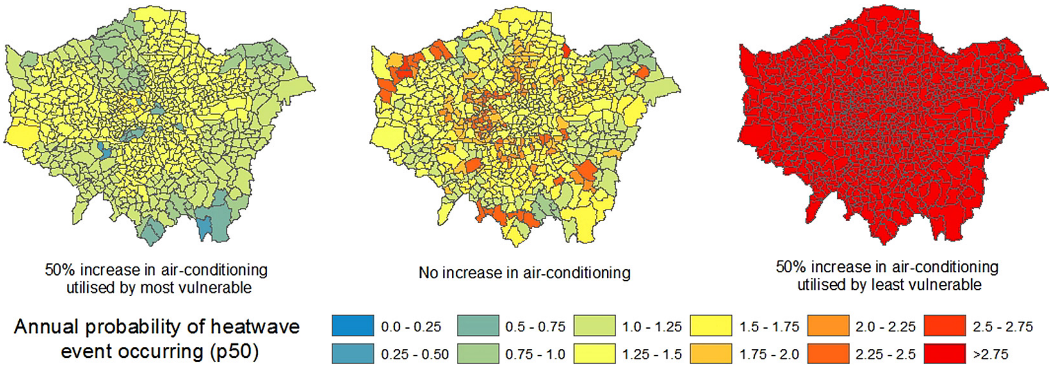

Fig. 8. Annual probability that 25% of residents will experience 5 consecutive days of residential overheating (2050s medium emissions scenario p50) for 3 air-conditioning scenarios.

3.1.3. Upgraded building stock

Our results show that upgrading London's building stock so every building's overheating performance is equivalent to the current best performing archetype for a given building type will be insufficient to maintain existing levels of overheating risk in the 2030 s and beyond. However, it would reduce projected residential overheating risk more than increasing urban greening by 50%. Fig. 9 outlines future overheating risk results per ward for a Level 1 Heatwave, Table A in the Supplementary materials outlines the changes in overheating risk with and without building level adaptation, averaged across London.

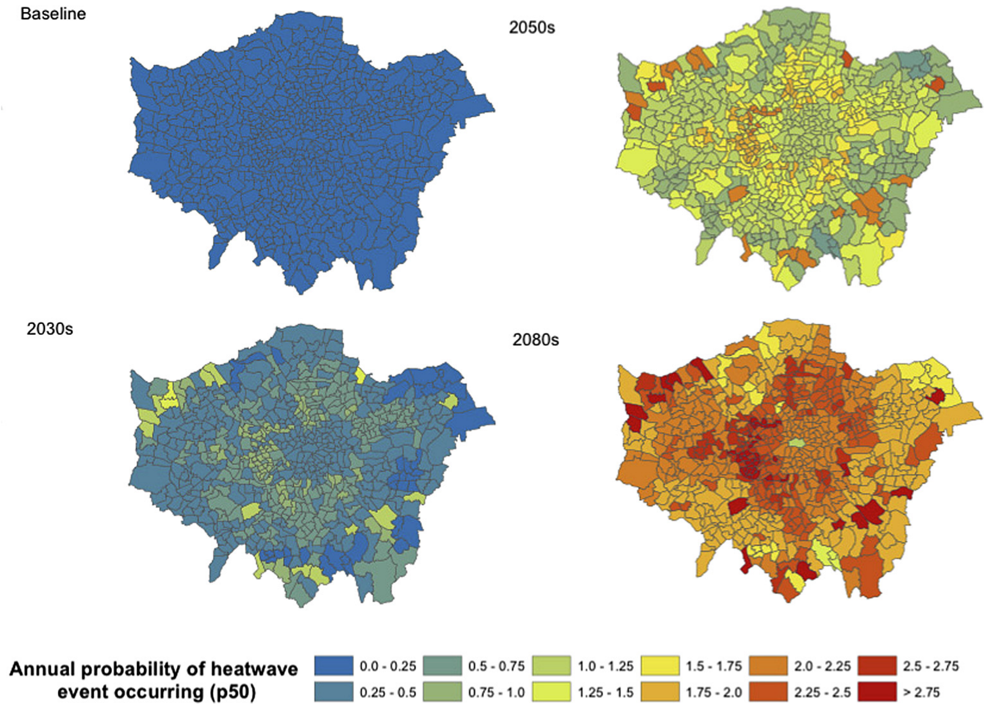

Fig. 9. Impact of upgrading 100% of the building stock on the annual probability that 10% of residents will experience 5 consecutive days of residential overheating (Level 1 heatwave) (medium emissions scenario p50).

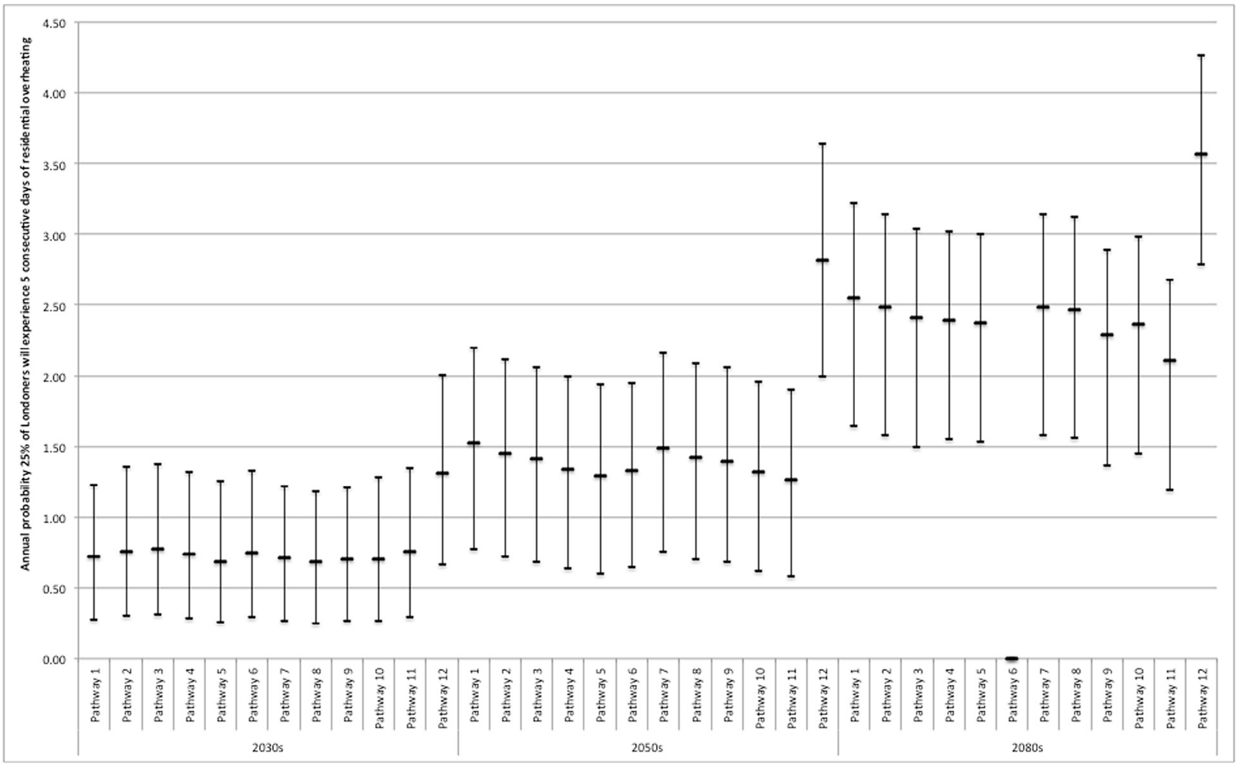

Fig. 10. Annual probability that 25% of residents will experience 5 consecutive days of residential overheating for each adaptation pathway (Level 2 heatwave).

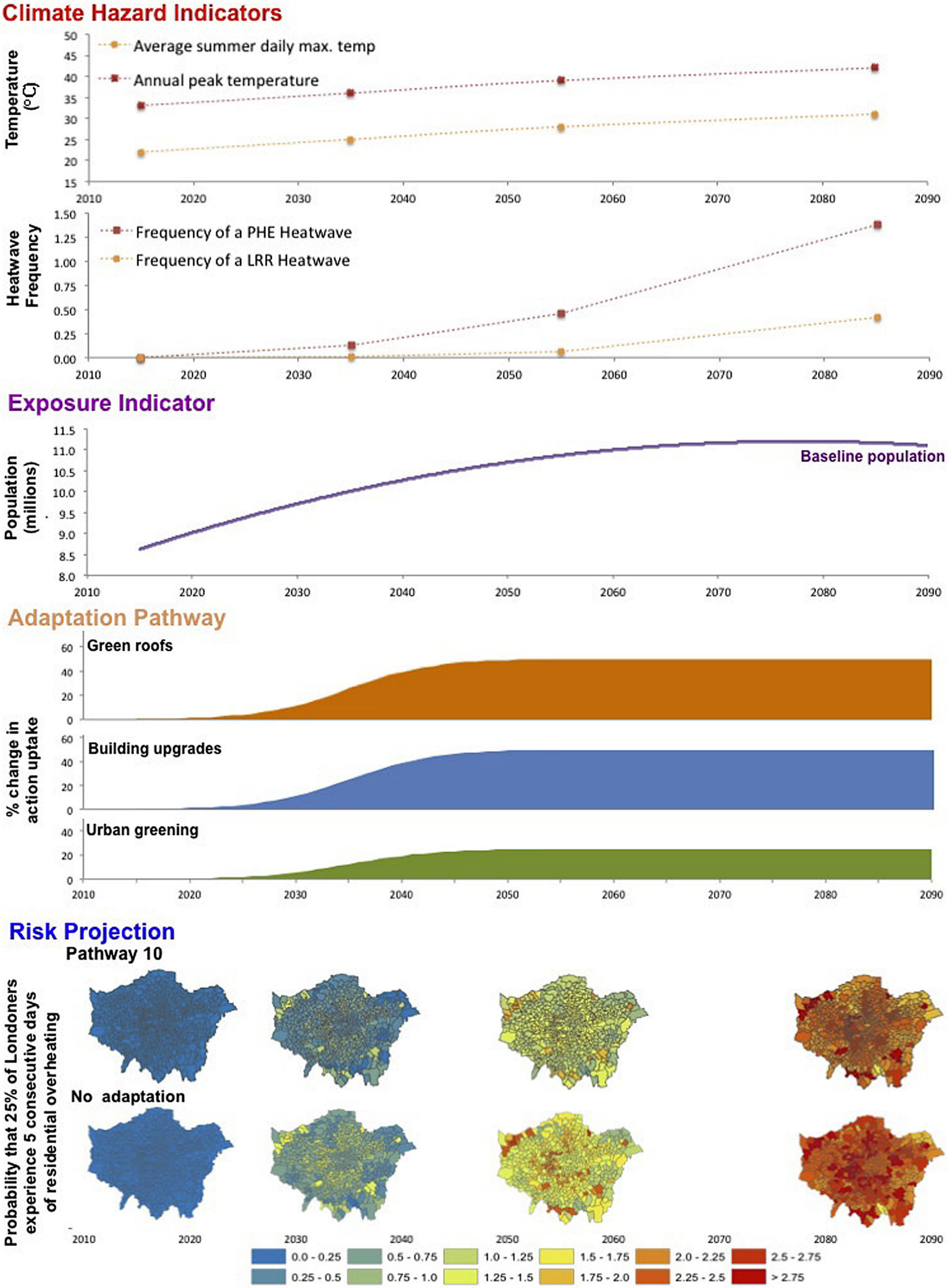

Fig. 11. Adaptation Pathway 10 diagram.

3.2. Adaptation pathways appraisal

Heat-risk was calculated at the ward level for the 2030s, 2050s and 2080s for each of the 12 demonstration pathways. Fig. 10 outlines the average projected Level 2 heat-risk across London with results for additional metrics included in the Supplementary material. Urban greening alone (Pathways 1–3) has a positive impact on reducing heat-risk compared to the no-adaptation scenario, but will not reduce the UHI enough to offset the impacts of climate change even under the extremely optimistic uptake scenario represented in Pathway 3.

Pathways 4, 5 and 6 are scenarios of varying uptake and access to air-conditioning. Pathway 4 assumes that uptake of air-conditioning is evenly distributed and follows the temperature-based uptake described in Table 7, which results in lower levels of risk than the no-adaptation scenario but higher levels of risk than the baseline period. Pathway 6 assumes that uptake of air-conditioning is evenly distributed and the uptake follows a logistic uptake curve peaking at 100% in 2100. This results in similar levels of risk to Pathway 4 in the 2030s and 2050s but it is effectively reduced to 0 once 100% air-conditioning uptake is achieved. Pathway 5 assumes air-conditioning is utilised by the most vulnerable; this pathway has slightly lower levels of risk despite also having lower levels of air-conditioning uptake, compared with Pathway 4. In Pathways 4–6 serious concerns would need to be addressed regarding the potential increase in greenhouse gas emissions, the mix and the capacity of London's future energy generation system (Day et al., 2009).

Whilst building-scale adaptation has been demonstrated in modelling studies to deliver adaptation benefits (Porritt et al., 2012; Mavrogianni et al., 2012), it has not at the city scale. As demonstrated in Pathways 7–9, at the city scale this would require improvements in the existing building stock, with thermal performance improving beyond that which is observed in London's existing building stock. This would also require building level retrofits to be undertaken faster than existing stock replacement rates.

In the 2080s upgrading or replacing 100% of the building stock, as per Pathway 9, was found to be more effective in reducing residential overheating, than a strategy that upgraded or replaced 50% of dwellings but also increased in urban green space by 25% and green roof area by 50%, as per Pathway 10. However, by including a portfolio of actions Pathway 10 is potentially more robust than Pathway 9, as it is less reliant on the effectiveness of a since action to manage heat risk. Pathway 10 will also deliver other co-benefits associated with urban greening.

Beyond air-conditioning all of London, as per Pathway 6, Pathway 11 is the most effective in reducing heat risk in the 2080 s, it assumes that there will be a 50% increase in urban green space, 82% of roof area will be converted to a green roof and 100% of buildings will be replaced or retrofitted. This would reduce the probability of Level 2 heatwaves by 0.3 in the 2050 s and 0.48 in the 2080 s, compared to the no-adaptation scenario. However, even following Pathway 11, heat-risk will continue to rise in each future time period compared to the baseline. This suggests that if existing levels of heat risk are not to be exceeded that additional adaptation measures would be required beyond the actions included in Pathway 11.

Pathway 12 explores an alternate less optimistic future and demonstrates potential increases in heat-risk from future reduction in levels of urban greening, in addition to increases in air-conditioning uptake by residents not considered vulnerable to heat-risk. This is estimated to increase the annual frequency of a Level 2 heatwave by 1.25 in the 2050s and 0.98 in the 2080s. Pathway 12 brings forward heat-risk by more than 30 years, as shown in Fig. 10 the level of heat-risk in 2050 exceeds the risk level in Pathways 1–11 in the 2080s.

Pathways diagrams were developed for the 12 pathways that bring together indicators for four attributes of climate-risk that change through time: (1) indicators of the changing climate hazard; (2) an exposure indicator; (3) a dynamic adaptation pathway; and (4) quantified indicators of climate-risk. The time dimension provides a sense of the temporal scale at which a pathway is applicable, which assists decision makers in visualising the dynamic risk. Fig. 11 is an example pathway diagram, highlighting Pathway 10.

4. Discussion and conclusions

This research proposes a new approach to manage long-term heat-risk at the city scale through demonstrating an adaptation pathways approach in London. A pathways approach contributes to the development of dynamically robust plans by incorporating flexibility in the scheduling and implementation of actions, and allowing changing levels of risk to inform future decisions.

Considering heat-risk at the city scale requires some simplifying assumptions compared with building or neighbourhood-scale analysis, however it is at the city scale that many critical decisions are made which affect future heat-risk, including land-use planning and building regulations. In London, for example, the GLA have a mandate to manage heat-related climate-risk (HM Government, 2007) but they have limited tools that assist them in quantifying the potential effectiveness of adaptation actions.

Our approach is complementary to approaches developed by Wolf and McGregor (2013) and Taylor et al. (2015) to understand existing vulnerability and climate-risk. However, a long-term approach provides additional value given the projected future scale of heat-risk and the need for planned adaptation (Jenkins et al., 2014b). Actions that alter the fabric of a city are typically challenging and slow to implement but they have long-term implications (Hallegatte and Corfee-Morlot, 2010). A long-term plan reduces the likelihood of mal-adaptation and undesirable lock-in, creates awareness of the dynamic nature of the climate system, and builds the political and business case for integrating flexibility into planning (Ranger et al., 2013).

Whilst building type has been found to have a greater influence on existing heat-risk than the UHI (Taylor et al., 2015; Oikonomou et al., 2012; Mavrogianni et al., 2011), there has been limited research that appraises the effectiveness of building-level adaptation compared with urban greening or air-conditioning at the city scale under future climate scenarios. This research addresses the need for climate change risk assessment to incorporate the appraisal of the effectiveness of adaptation actions. This has allowed us to better understand the potential effectiveness of a range of portfolios of actions that may or may not be proportionate to the scale of the adaptation challenge. The results have highlighted the limitations of adaptation strategies that focus solely on urban greening or building-level adaptation that does not improve beyond the best performing buildings within London's existing building stock. We have demonstrated the impact of increasing heat emissions from air-conditioning on the UHI and the possible negative consequences.

This research highlights the scale of the heat-risk adaptation challenge facing London and demonstrates the potential of a pathways approach, using new and existing indicators of heat-risk. Our results reveal that heat-risk will not be maintained at existing levels by the portfolios of adaptation actions identified, unless supplemented by air-conditioning. However, if Londoners' successfully exhibit physiological acclimatisation and/or behavioural adaptations, the rate of mortality per degree rise in temperature may be lower than reflected through historical mortality response functions (Stone et al., 2014), and residential overheating risk may be lower than that reflected through an absolute overheating limit (CIBSE, 2013).

The development of pathways diagrams has been a key component of the research. They contribute to communicating the potential scale of the challenge and the value in adopting a flexible approach to climate-risk management that is informed by effective monitoring and evaluation (Reeder and Ranger, 2011; Kingsborough et al., 2016). Initial stakeholder feedback found the pathways diagrams to be a potentially valuable input to long-term planning. However, the application of a risk-based approach to the development of adaptation pathways for heat-risk remains challenging. From an institutional perspective, managing heat-risk is difficult given the limited statutory requirements to manage urban heat-risk beyond heatwave response planning (Zaidi and Pelling, 2015). This further compounds challenges associated with defining tolerable levels of heat-risk and trigger values for adaptation action, as they relate to each metric for urban heat-risk. Identifying indicators that are informative, measurable and relevant to a wide range of stakeholders is also a challenge that needs to be addressed to operationalise a pathways approach.

To further develop adaptation pathways in response to heat-risk in London there is a need to identify adaptation portfolios that are proportionate to the projected future levels of risk. Future portfolios may include additional actions identified in Fig. 2 including building design actions in combination with an increased range of behavioural responses. Overheating risk metrics may be modified to include additional social and demographic information so that underlying vulnerability is accounted for. This research would be complemented by further stakeholder consultation and potential co-development of pathways. This process could be used to facilitate a dialogue regarding tolerable and acceptable levels of heat-risk and linkages to monitoring and evaluation.

We have appraised adaptation actions and pathways in terms of their effectiveness at reducing mortality and managing residential overheating at the city scale, however we acknowledge that city-level decision makers will need to consider a broader range of criteria including cost-effectiveness, equity, greenhouse gas emissions, socio-political acceptability, flexibility and robustness.

Our integrated modelling approach is beneficial in that it facilitates the consideration of a range of impacts and adaptation options within a single framework. Spatially coherent time-series data allowed us to map and identify high risk wards in each time period, however the framework may be updated to incorporate transient climate change projections (Glenis et al., 2015). The use of transient scenarios would allow decision rules to be incorporated endogenously, based on triggers values.

We utilised the UKCP09 probabilistic climate change projections that reflect the stochastic nature of weather and allow for climate model uncertainty to be explored, however we have only used a single emissions, population growth and land-use change scenario. An increased set of scenarios or robustness testing of assumptions and uncertainties could be used to better understand the robustness of proposed adaptation pathways. Given our results however, priority should be placed on quantifying the effectiveness (and sensitivity to key assumptions) of an increased set of adaptation actions.

This research has demonstrated an innovative approach to the development of adaptation pathways that respond to projected increases in heat-related mortality and residential overheating. We have quantified how risk varies for a range of adaptation pathways through time with climate change and population growth and we have demonstrated how spatially coherent downscaled probabilistic climate change projections that account for changes in urban land cover and the anthropogenic heat flux can be used to inform adaptation planning to the 2080s.

Heat-risk management will become increasingly important in London and processes to manage trade-offs will need to be established so that necessary actions may be implemented. There is significant potential for a pathways approach to be used in adaptation planning for heat-risk in cities globally, with the degree of quantification dependent on institutional capacity and data availability. This adaptation pathways approach complements long-term planning for flood (Reeder and Ranger, 2011) and water-supply risk (Kingsborough et al., 2016), and demonstrates an effective framework for informing long-term adaptation planning for heat-risk.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.crm.2017.01.001.

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