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Review article

Indicators to support local public health to reduce the impacts of heat on health

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ABSTRACT

Heat exposure presents a significant weather-related health risk in England and Wales, and is associated with acute impacts on mortality and adverse effects on a range of clinical conditions, as well as increased healthcare costs. Most heat-related health outcomes are preventable with health protection measures such as behavioural changes, individual cooling actions, and strategies implemented at the landscape level or related to improved urban infrastructure.

We review current limitations in reporting systems and propose ten indicators to monitor changes in heat exposures, vulnerabilities, heat-health outcomes, and progress on adaptation actions. These indicators can primarily inform local area decision-making in managing risks across multiple sectors such as public health, adult and social care, housing, urban planning, and education. The indicators can be used alongside information on other vulnerabilities relevant for heat and health such as underlying morbidity or housing characteristics, to prioritise the most effective adaptation actions for those who need it the most.

1. Introduction

Projected increases in the frequency of heatwaves (extended periods of hot weather) in the UK means that heat-related health events will also rise in the absence of effective adaptation. Future projections of temperature-related mortality in the UK show heat-related deaths could range from 7,000 to 11,000 deaths per year by mid-century, from a current annual average of 2,000 deaths (Hajat et al., 2014; UKHSA, 2023). This will likely put significant strains on the delivery of health and social care services. Many adverse health events are preventable with local health protection measures, however, the absence of suitable indicators renders local response teams and decision makers ill-equipped to prioritise actions, as they are unable to appropriately track the impacts of climate change on health or assess progress on adaptation efforts.

Well-functioning health information systems (HIS) (WHO, 2015) can support the health sector and societies to attain climate resilience by i) providing information on vulnerability to climate risks, ii) tracking and demonstrating the ability to manage climate-related risks iii) integrating climate information into disease surveillance to develop early warning systems and targeted interventions, and iv) incorporating the rapidly emerging body of research on health impacts of climate change (WHO, 2015). Indicators contribute to HIS functionalities towards supporting the climate resilience of health systems; indicators can assess the systems' ability to anticipate, respond and adapt to, and recover from climate-related shocks whilst ensuring sustainable improvements in population health. To do this, indicators need to be well designed to ensure they are scientifically valid for tracking risk and are useful for informing and driving local action (Ebi et al., 2018).

The UK Climate Change Committee (CCC), an independent statutory body established under the Climate Change Act 2008, has developed indicators to track adaptation nationally and by sector (CCC, 2022). The

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CCC has an important role in assessing whether current levels of action are sufficient to manage climate risks to an acceptable level of impact. These indicators however fall short of adequately monitoring the health risks associated with heat due to a lack of appropriate datasets and information systems. These challenges are not unique to the UK; an assessment of the impacts of climate change on human health in the US (Crimmins, et al., 2016) supported the development of new indicators to address heat-related health risks (CDC, 2020).

Other challenges are related to poor integration between health and policy areas that support climate adaptation. In the UK, barriers to effective local action include a lack of clear agency to promote health concerns in other sectors (Woodhall et al., 2021), as actions fall within the remits of a wide range of departments. Heat risks to populations are modified by the natural and built environment, including housing quality and spatial planning decisions (Kovats and Brisley, 2021; Murage, 2020). Health service delivery and social care adaptation include a range of actions and processes that should minimise negative health events associated with climate change, optimise co-benefits, and strengthen the capacity to maintain quality care in a changing climate (England, 2021), however, some of these actions fall outside the remit of 'health systems and services'. As a consequence, there are significant variations in the level of adaptation implementation across the health system in the UK, including the implementation of public health action and priorities within Local Authorities' (LAs') climate action plans (Climate Emergency UK, 2022). Closer integration across relevant areas of responsibility can help deliver policies that support adaptation and information systems used by LAs across their policy areas (including housing, transport, and education) that have value for public health action.

The objective of this paper is to demonstrate the process of developing a set of indicators that can be used by local teams to monitor heat exposure, vulnerability to heat, impacts of heat on human health, and progress on the implementation of adaptation actions. Increasing temperatures and more frequent and intense heatwaves will likely impact service provision across multiple sectors, which creates a need for indicators that can support comprehensive intersectoral collaboration to address climate change health risks and monitor progress on adaptation. This paper focuses on heat-related risks as this is one of the largest weather-related cause of death in high-income countries (Ebi, 2021), although we acknowledge there are many other climate change risks to health as identified by the UK's Third Climate Change Risk Assessment (CCRA) (CCC, 2017).

2. Methods

Developing the indicator set was a three stage process that included: 1) consultation with local authority public health teams through two stakeholder workshops held in May 2021 and March 2022, the purpose of which was to identify priority indicators for local area use, 2) reviewing existing literature to identify current and potential indicators that can support intersectoral programmes to protect and improve population health against climate-related risks, and 3) obtaining expert opinion to propose indicators where there were gaps. The work led to the identification of over 60 indicators potentially useful to assess health implications of climate risks or climate actions (UKHSA, 2023). This paper builds on this work and reports a subset of the most relevant indicators that were associated with heatwaves and heat risk to health (UKHSA, 2023).

The indicator selection process was informed by the DPSEEA framework (Niemeijer and de Groot, 2008; Hambling et al., 2011) which helped define causal links between indicators by grouping them into exposure/hazard, vulnerability, outcomes/impact and action/process. Exposure/hazard is defined as conditions that create potential for exposure to hazardous conditions (e.g. increase in temperature), vulnerability includes factors that strongly affect risks and increase the likelihood of negative health outcomes, outcome/impact is the experienced effects on human systems that can be attributed to the exposure, and process/action are measures taken to reduce exposure or vulnerability, or to minimise the outcome/impact. Identifying these inter-relationships between the indicators was a part of the indicator selection process, it provided transparency and structure, which addressed some common criticisms of the selection process (Niemeijer and de Groot, 2008). The use of public health engagement, evidence review and expert consultation led to the proposal of ten indicators (aligned with DPSEEA) that can support local authorities and partner organisations to minimise heat-related health risks by 1) monitoring changes in known exposures, 2) assessing local vulnerability, 3) quantifying impacts of heat-related illness and deaths, and 4) evaluating the progress of implemented adaptation actions across multiple sectors.

Once the indicators were identified, we adapted an existing tool (Niemeijer and de Groot, 2008) to define core indicator characteristics across five dimensions (Supplementary Table S1). We thereafter sought input from subject experts to assess how the indicators met these characteristics in relation to linkages to scientific evidence and specifically with regards to sensitivity to health outcomes, we also examined the relevance to policy in terms of acceptability by stakeholders, measurability and scale to ensure data are available at the relevant local or regional level, the feasibility of indicator development based on availability of data, and lastly, robustness, or the ability to respond in a predictable manner to changes and to be insensitive to expected sources of interference (Niemeijer and de Groot, 2008). The final set includes some indicators that already exist, some that can be made available with some data acquisition and processing, and several that require more extensive work to develop. All the study co-authors provided subject expertise on the indicators that aligned with their work.

3. Results

The section below details how these indicators meet the core characteristics across the five dimensions and provides more information on indicator readiness. It is unlikely for the indicators to meet all the identified qualities, but a good indicator should aim to achieve most. In Fig. 1, we use a traffic light system to summarise the findings. Green suggests the requirements of the dimension have been met or exceeded. Orange suggests the indicator needs further work to meet the assessed dimension, but this does not affect the indicator use. Red suggests extensive work is needed to develop the indicator to meet the requirements of the given dimension. More information on the indicators' immediate availability is provided as follows: **DA-U (Data Available & Used)** means that data to develop the indicator are readily available and the indicator is currently in use, **DA-P** indicates data is available but **'Processing'** is required, and **DU** indicates data is **'Unavailable'.**

3.1. Indicators of exposure

1. **Annual number of hot days with regards to regional temperature threshold (coloured dots correspond to Fig. 1 and show how the indicator meets the core characteristics)** ● ● ● ● ●

Sensitivity to health outcomes: There is very good evidence showing how exposure to high temperatures and associated heat stress can increase mortality and morbidity as well as reduce workplace productivity and cognitive performance (Ebi, 2021). The impacts on health are acute during a heatwave with illness and death possible among the fit and healthy, and not just in high-risk groups (UKHSA, 2022).

Policy relevance: Daytime and night-time regional temperature thresholds have been used by the Met Office National Severe Weather Warning Service (NSWWS) when deciding whether to issue a heatwave warning (UKHSA, 2022). These threshold values have been previously assigned based on increased risks to health (e.g. 32 °C maximum temperature for London) (UKHSA, 2022). The indicator could be the number of days when these thresholds are exceeded, and these may be

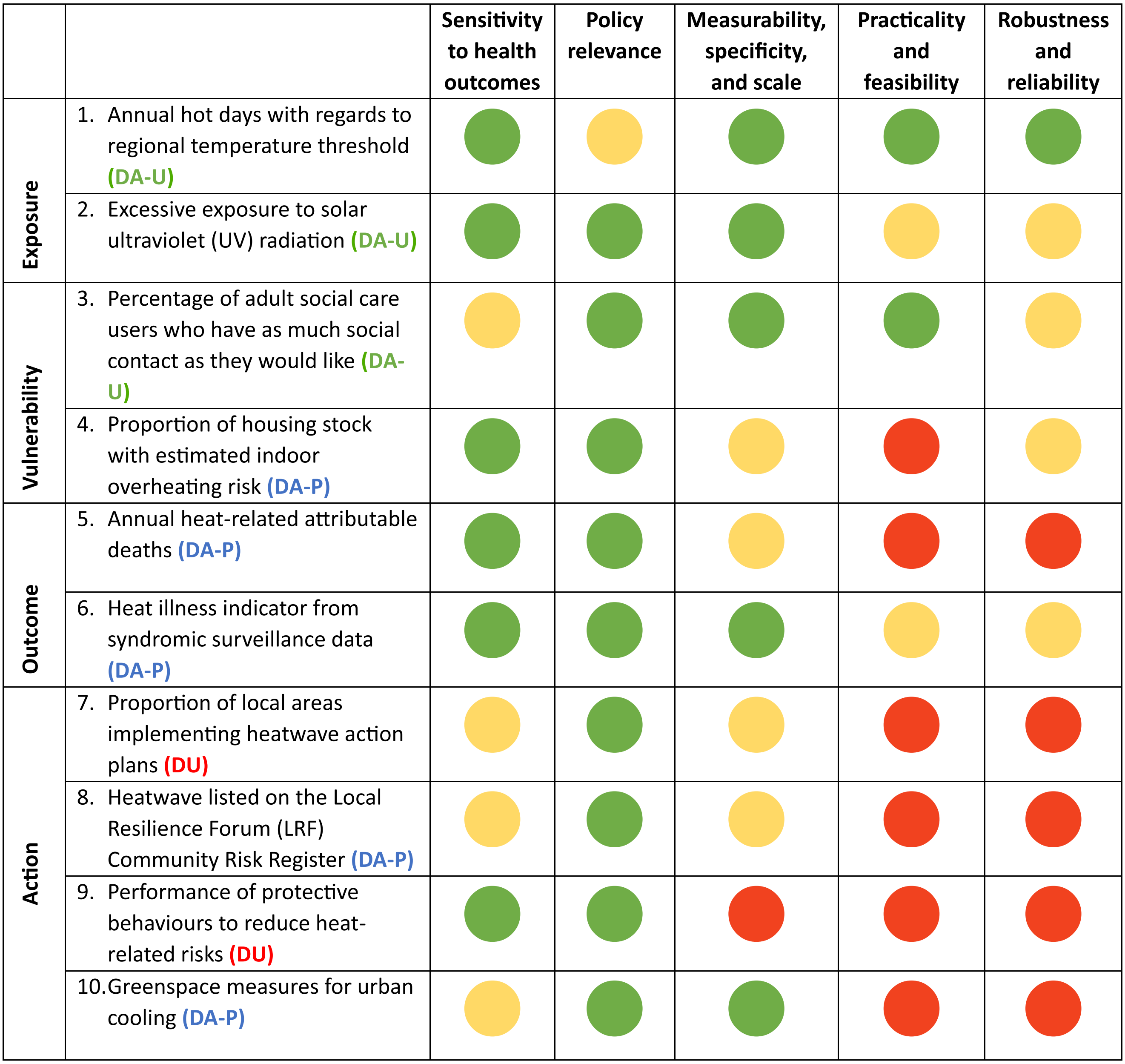

Fig. 1. A traffic light system to classify the indicator readiness as per the selection criteria.

periodically re-evaluated as alerting and response plans are updated. In the UK, national heatwave warnings have moved to a more impact-based system (as opposed to absolute threshold values only) although regional thresholds are likely to still be incorporated in decisions on heat alerting (Adverse Weather and Protecting, 2023).

Measurable, specificity and scale: The indicator can be derived in various ways and at the desired scale. This involves identifying a population-level threshold for heat impacts, locally determined thresholds may be more relevant than those issued regionally and can be derived in several ways: a) epidemiological thresholds specific to the population of interest, b) extreme heat thresholds (based on human physiology) which have general applicability, c) operational thresholds, for example as used by the previous England heat-alert system (UKHSA, 2022).

Practicality and feasibility: Data required to develop this indicator are readily available but require some processing. Appropriateness of heat metrics for health outcomes will vary by how temperature is measured; ambient daily mean, minimum or maximum temperature or WBGT (wet bulb globe temperature). There are various sources of heat exposure datasets, most are free to use although some require approval for server access. A list of some common sources is given in the supplementary information (Table S2).

Robustness and reliability: This is a robust indicator that is not sensitive to any known sources of interference e.g. changes in monitoring programs that can interfere with how data are collected. Temperature data and other meteorological variables are subject to national and international standards such as the World Meteorological Organisation (WMO) guidelines that maintain data quality and integrity.

2. **Excessive exposure to solar ultraviolet (UV) radiation**

Sensitivity to health to health outcomes: Excessive exposure to sunlight increases the risk of skin cancers, sunburn (erythema), cataracts, premature skin ageing and a weakened immune system (Lucas, et al., 2006). However, insufficient sunlight can also have health consequences (Alfredsson, 2020) and may result in a burden on health services (Rendell et al., 2020; Lucas et al., 2010). Sunlight increases vitamin D and promotes healthy bones, improves cardiovascular and metabolic health, may reduce the risk of some cancers, and is essential for melatonin regulation for better quality sleep and serotonin regulation for improved mental health (Holick, 2016; Holick, 2004; Liu, 2014; de Vries et al., 2007; van der Rhee et al., 2016).

Policy relevance: WHO and WMO have developed a UV index which indicates the risk of sunburn between 0 and 20 and provides advice on when to take more protective actions. Ambient temperature is not directly correlated with environmental levels of UV, although temperature may influence behaviours such as time spent outdoors (Soueid, 2022) and the type of clothing worn, which in turn affects exposure to UV. The health implications of sun exposure are dependent on behaviour and vary by socio-demographic variables such as skin colour and age. In England, UV levels peak around June, while peak temperatures are normally at least a month later. Cooler temperatures in the spring are wrongly perceived to carry a low UV risk, even though the risk may be higher than in peak summer when heatwave warning systems are likely to be triggered (Baczynska et al., 2019).

Measurable, specificity and scale: UKHSA has been undertaking ground-based measurements of erythema effective UV, UV type A irradiances and illuminance for over 30 years from 10 ground-based sites (Defra, 2022). Erythema effective UV (McKinlay and Diffey, 1987) is used to determine the risk of causing sunburn which is simplified for the public in the form of the UV Index. Impact on health is determined by sunlight exposure as well as by behaviour and socio-demographic profiles.

Practicality and feasibility: Environmental data required to develop this indicator are readily available but require processing depending on the data source (ground-based or satellite) for local area use. UKHSA monitors UV radiation and displays near real-time UV Index to the public (Defra, 2022). Forecasts of UV index are based on Earth observation satellite data, which includes the effects of cloud cover and ozone (Met Office, 2022).

Robustness and reliability: Ground-based solar UV radiation is routinely measured with detectors that adhere to national standards. Data obtained from Earth observation satellites to forecast the weather are robust and reliable. Impacts on health due to sunlight exposure are less reliable because these are dependent not only on the environment but on behaviour and socio-demographic factors.

3.2. Indicators of vulnerability

3. **Social isolation: percentage of adult social care users who have as much social contact as they would like** ● ● ● ● ●

Sensitivity to health outcomes: Social isolation interconnects with other factors such as age, health status and living environment to increase vulnerability to heatwaves. Emerging evidence suggests interventions on social isolation could limit the impacts of heatwaves on the elderly population (Orlando, 2021), in particular those living in urban areas (Kim et al., 2020). More UK focused research is needed to identify other at-risk groups and appropriate points of intervention.

Policy relevance: Tackling loneliness and social isolation and supporting people to develop and maintain social connections is a key Government vision for social care because of the known links between social isolation and poor mental and physical health (Department of Health and Social Care, 2018), which are well documented heat-health outcomes (Kovats and Hajat, 2008).

Measurable, specificity and scale: The indicator is well defined and available for local area use. The data presented for LA use is not stratified by age even though older adults are more at risk from both social isolation and consequently from heat risk, however, it may be possible to extract this information from the Adult Social Care Survey.

Practicality and feasibility: Data are routinely collected by the annual Adult Social Care Survey. No further processing is required as they are already part of the Public Health Outcomes Framework (PHOF) (Office for Health Improvement and Disparities, xxxx) and Adult and Social Care Outcomes Framework (ASCOF) (NHS Digital, 2021).

Robustness and reliability: This is a fairly robust indicator and has been assessed during PHOF/ASCOF development. It has a proven track record and has been in use for several years. There are however some issues that may affect its use, for example, it is based on the adult and social care survey which has a response rate of only 46 % which may introduce some bias in addition, the indicator does not cover isolation in the broader population but rather focuses on social care users only.

4. **Proportion of housing stock with estimated indoor overheating risk** ● ● ● ● ●

Sensitivity to health outcomes: Indoor overheating, defined as the state at which occupants experience thermal discomfort due to the indoor environment, has been linked with reduced productivity, cognitive performance, sleep quality, and overall dissatisfaction with the indoor environment (Lan et al., 2011; Okamoto-Mizuno and Mizuno, 2012). Indirect evidence suggests adverse impacts on heat-related morbidity and mortality from exposure to high indoor temperatures (WHO, 2018). The CCC assessment of UK climate risk considers health risks posed by indoor heat exposure as one of the areas needing the highest priority for adaptation (Committee on Climate Change, 2021).

Policy relevance: The indicator can be used to monitor the prevalence of indoor overheating risk, changes over time due to climate change, and physiological, behavioural, or policy-driven adaptation. It has been used in such a capacity – at the national level – by the relevant departments of the UK government following the completion of the 2011 and 2017 Energy Follow-Up Surveys (Hulme and Beaunmont, 2011; BEIS, 2021).

Measurable, specificity and scale: It is possible to derive this indicator through an empirical approach to quantify the proportion of housing stock that overheats by collecting data from a representative sample of homes, either using thermal comfort surveys, indoor temperature monitoring, or both. Alternatively, the indicator could be estimated from a modelling approach using machine learning or building physics-based tools.

Practicality and feasibility: The empirical approach is likely to result in a more accurate estimation since it would not be influenced by uncertainties common to modelling procedures. However, this requires systematic data collection which can be costly. Modelled estimates are more feasible; the data required as model inputs such as from the English Housing Survey or the Energy Performance Certificate dataset are already available (Supplementary Table S2), although a significant constraint is in the use of specialist software and expertise in building physics. A cost-effective approach would be to use a combination of modelling and empirical approaches.

Robustness and reliability: The concurrent monitoring of indoor temperatures and perceived thermal comfort would make this a robust and reliable indicator. Currently, assessing overheating risk using indoor temperatures relies on the use of overheating metrics. The efficacy of such metrics when applied in domestic settings is contested (Petrou et al., 2019) due to bias in thermal comfort surveys, for example, those more vulnerable to heat (such as the elderly) are less likely to perceive and report indoor overheating (Lomas, 2021). Collecting data on indoor temperature and perceived thermal comfort can enable the refinement of existing overheating metrics.

3.3. Indicators of outcome

5. **Annual heat-related deaths** ● ● ● ● ●

Sensitivity to health outcomes: Health outcomes such as mortality or morbidity increase above given temperature thresholds. The relationships between these outcomes and temperature are derived by epidemiological analysis and reported either as risk of outcome (relative risk) or odds of outcome (odds ratio). In the UK, the heat-health effect generally increases at around the 93rd percentile (Armstrong, 2011) of the temperature distribution of annual daily mean temperatures (approximately 18 °C in London). Risk generally varies with age and underlying illnesses. (Kovats and Hajat, 2008).

Policy relevance: Quantifying the mortality burden of higher temperatures is important for public health decision making and can inform health protection and planning of effective responses. UKHSA and partner agencies provide information on excess mortality occurring during heatwaves (periods where an alert level 3 or higher has been issued) (UKHSA, 2022; UKHSA, 2022). There is a need for an indicator to routinely monitor mortality burdens outside heatwaves since the greatest health burdens associated with heat are thought to occur outside of the alert periods (Agency and Effects, 2012; Policy Innovation and Evaluation Research Unit (PIRU), 2019).

Measurable, specificity and scale: Attributing heat exposure to health outcomes at the local area level may lead to imprecision because of the small numbers observed in some areas. Previous work in the UK has reported effect sizes at a national and regional level (Hajat et al., 2014), across cities (Gasparrini, 2015) or by daytime vs. night-time (Murage et al., 2017). In the UK, heat risk varies by region, with London experiencing the greatest risk (Hajat et al., 2014).

Practicality and feasibility: A commonly applied metric for estimating heat risk is the relationship between daily mortality counts and daily changes in ambient temperature over several years. A more meaningful metric for local users is the 'heat attributable fraction' which uses heat risk to estimate the population burden or total attributable number of deaths caused by non-optimum temperatures (Gasparrini, 2015). Processing requires expert use of statistical software and some knowledge of epidemiology.

Robustness and reliability: This indicator shows how temperature increases contribute to increases in heat-health effects and can indicate the annual health burden of high temperatures at the local level. It is less reliable when projecting future health burdens under climate change scenarios because risk functions change over time and are influenced by adaptation and acclimatisation which is challenging to estimate accurately.

6. **Heat illness indicator from syndromic surveillance data** ● ● ● ● ●

Sensitivity to health outcomes: Hot weather has a range of effects on illnesses characterised by increases in counts of general practitioner in hours (GPIH), general practitioner out of hours (GPOOH), hospital admissions and ambulance dispatches. Many cases of heat-related illness bypass medical presentation because heat exhaustion can become acute very quickly if left untreated. A previous study found higher GPOOH and heat illness in children of school age (Smith, 2016), suggesting that parents are more likely to present their children earlier to healthcare services, while the elderly are likely to delay presentation to avoid burdening services. More morbidity studies and evidence is needed, for example, to understand what drives differential timing of presentations by different demographic groups.

Policy relevance: UKHSA collects information related to illness on a real-time basis through syndromic surveillance systems that include calls to NHS 111, GP consultations and emergency department attendances (UKHSA, 2022). Current evidence on heatwave impacts on health is dominated by mortality effects, however, the use of syndromic surveillance also offers opportunities to address the knowledge gap on the impacts of heatwaves on morbidity.

Measurable, specificity and scale: Syndromic surveillance is an important surveillance tool for monitoring public health in real-time and is used to monitor the health impacts of heatwaves. Heatstroke remains the most sensitive indicator for monitoring the impacts of a heatwave, however the number of cases are usually very low for local area use (Smith, 2016). Syndromes that may map to symptoms of heatstroke or heat exhaustion, such as difficulty breathing or fever, may be used as indicators; although these may not be sensitive enough to show any impacts during mild heatwaves (Smith, 2016).

Practicality and feasibility: The UK Health Security Agency's (UKHSA) real-time syndromic surveillance team (ReSST) collects and analyses data from various sources, and publishes regular bulletins to show any trends of higher-than-usual levels of illness (UKHSA, 2023). However, low numbers may impede local area use.

Robustness and reliability: The indicator is fairly robust and has been used before to show differential timing of presentations, for example, GPOOH and emergency department attendances were timely with respect to increases in temperature, but GPIH consultations reacted more slowly (Smith, 2016). More work is needed to understand these differences and to define common morbidity outcomes that are sensitive to heatwaves.

3.4. Indicators of action

7. **Proportion of local areas implementing heatwave action plans** ● ● ● ● ●

Sensitivity to health outcomes: An evaluation of the previous Heatwave Plan for England in 2019 found little evidence of the Plan's impact on mortality or hospital admissions since its introduction (Policy Innovation and Evaluation Research Unit (PIRU), 2019). However, other studies have shown that the implementation of heat wave warning systems (HHWS) (which are integral parts of heatwave plans) can be effective in preventing heat-related mortality and in reducing costs associated with treating heat-related morbidity (Toloo et al., 2013; Nitschke, 2016); with the benefits far outweighing the costs of operationalising a HHWS (Toloo et al., 2013).

Policy relevance: The Heatwave Plan for England (operational between 2004 and 2023) worked by triggering actions in the NHS, public health, social care and other community and voluntary organisations to support people who have vulnerability to heat, with the objective of reducing summer deaths and illness (UKHSA, 2022). Actions were triggered when temperatures reached defined thresholds which varied by region (e.g. 32 °C day and 18 °C night in London) (UKHSA, 2022). The Heatwave Plan was recently superseded by the Adverse Weather Health Plan (Adverse Weather and Protecting, 2023), an impact-based alerting system that promotes integrated arrangements to offer protection from weather-related harm and build community resilience (Adverse Weather and Protecting, 2023).

Measurable, specificity and scale: Although several key parts of the heatwave plans are implemented locally, details on local area implementation are not currently collected. In the UK, local areas are responsible for ensuring that preparedness and response plans are created, tested, and regularly monitored to ensure high quality services. An evaluation of the previous Heatwave Plan for England (Policy Innovation and Evaluation Research Unit (PIRU), 2019) conducted using in-depth interviews with key local authorities informants found that heatwaves were given lower priority on emergency preparation agendas because they were viewed as likely to be infrequent and short-lived. The evaluation found other natural hazards such as flooding and cold weather were given higher priority (Policy Innovation and Evaluation Research Unit (PIRU), 2019).

Practicality and feasibility: There are currently no data available to produce this indicator and work to develop it will likely require national coordination by public health agencies to gather information on whether local authorities have developed and implemented heatwave action plans, and more detailed information on the scale and context of implementation.

Robustness and reliability: A study comparing the predictive capacity of 4 different HHWS approaches found that triggering alert days and ultimately emergency action varied significantly by the approach used (Hajat, 2010). Refining this indicator to monitor quality requires incorporating some level of agreement between various HHWS approaches. This may include ensuring consistency in the core elements of a heat-health action plan including consideration of governance, accuracy and timeliness of the warning systems, and long-term planning among other factors.

8. **Heatwave listed on the Local Resilience Forum Community Risk Register** ● ● ● ● ●

Sensitivity to health outcomes: A Community Risk Register (CRR) is a multi-agency effort in a given area, highlighting emergencies/risks that have the highest likelihood of happening and their potential impacts on services and communities. It is generated by Local Resilience Forums (LRFs) which are multi-agency partnerships made up of representatives from Category 1 Responders (emergency services, local authorities, NHS, Environment Agency) and Category 2 responders (Highways Agency and public utility companies). LRFs work to produce emergency plans to prevent or mitigate the impacts of events which threaten human welfare, cause damage to the environment, or pose a security risk (Cabinet Office, 2013).

Policy relevance: Under the Civil Contingencies Act 2004, responders have a collective responsibility to plan, prepare and communicate in a multi-agency environment. The Act establishes a consistent level of civil protection activity across the UK and provides a basic framework defining what tasks should be performed and how cooperation should be conducted (Cabinet Office, 2012). A survey of members of Local Resilience Forums showed that heatwaves were the 'severe weather event' they felt least well prepared to deal with (Cox and Crouch, 2017).

Measurable, specificity and scale: The indicator would account for whether heatwaves are considered on the risk register (yes vs. no) and the position of heatwaves on the matrix (low, medium, high). This information indicates the level of prioritization (including resource allocation) when managing heatwaves. The risk assessment process is defined in the guidelines on emergency preparedness (Cabinet Office, 2012) which to some extent reduces subjectivity in assigning risk status. A total of 42 LRFs have been established and serve communities defined by the boundaries of Police Areas across England and Wales (Cabinet Office, 2013).

Practicality and feasibility: Category 1 responders have a duty to publish the CRR to increase awareness to communities and businesses. All CRRs are publicly available but would require resources to systematically access the information and generate the indicator.

Robustness and reliability: It is unclear how regularly the register is updated as there is no statutory requirement for a regular review of risks. The national recommendation is for the reviews to align with the annually updated government Local Risk Assessment Guidance (LRAG) (Cabinet Office, 2012).

9. **Performance of protective behaviours to reduce heat-related risks** ● ● ● ● ●

Sensitivity to health outcomes: People's behaviour during heatwaves can impact their risk of experiencing negative health symptoms. Heatwave and adverse weather plans include messaging to inform the public about personal heat risk and to promote the uptake of protective behaviours. Perceptions of heat-health risks and uptake of protective behaviour amongst vulnerable populations is affected by factors such as the presence of co-morbidities, perception of severity of weather and locus of control (Abrahamson, 2008; Wolf et al., 2010). Other factors such as individual capability, opportunity, and motivation also play a role in behaviour change (Michie et al., 2011).

Policy relevance: Understanding the factors that determine behaviour change and uptake of adaptation measures is crucial to tailoring interventions to relevant target groups, for example older adults (Lowe et al., 2011). Identifying and tracking protective behaviours is an important aspect of evaluating the success (or lack of success) of early warning systems such as the Heat-Health Alert Service. Equally, targeting beliefs and attitudes that may prevent individuals from perceiving themselves to be at increased risk has been used as a means of influencing behaviour change in the most vulnerable (Gaube et al., 2019).

Measurable, specificity and scale: This indicator could focus on behavioural modification during hot weather, assessed via self-report questionnaires and qualitative interviews (Abrahamson, 2008; Bittner and Stößel, 2012; Mattern et al., 2000; Richard et al., 2011). Constructs from the Health Belief Model (Rosenstock, 2000) and Theory of Planned Behaviour (Ajzen, 1991) have been previously adapted to generate Likert scale-item and open-ended questionnaires examining heat risk perception and behaviours (Richard et al., 2011; Valois, 2020; Akompab, 2013). Risk perception is necessary for enabling behavioural uptake, but an indicator focusing solely on this is insufficient as it does not indicate uptake of adaptation measures or modification of behaviour.

Practicality and feasibility: An indicator to measure behaviour changes during hot weather is presently not available but could be developed using a validated questionnaire, or, by incorporating relevant questions to assess the uptake of protective behaviours into an existing national survey (such as the UK General Household Survey). Alongside this, it would be feasible to develop a metric to routinely evaluate the impacts of heat-health action plans (or any public health messaging) on increasing public awareness and uptake of protective behaviours.

Robustness and reliability: Objective data are the gold standard measurement to indicate changes in the adoption of protective behaviours, such as air conditioning use by different demographic groups, although it would not tell us anything about levels of awareness of the risk. A complementary indicator to measure the perception of heat risk is required to attribute behaviour change to population awareness and enable the evaluation of heat awareness interventions.

10. **Greenspace measures for urban cooling** ● ● ● ● ●

Sensitivity to health outcomes: Green Infrastructure (GI) such as parks, gardens, street trees, wetlands and green roofs/walls can offer sustainable low-cost cooling strategies for cities (Jay, 2021). Urban environments with higher vegetation cover are observed to be markedly cooler and may experience lower heat-health burdens (Murage, 2020). Cooling increases with the size, volume and structure of vegetation cover; layers of trees and shrubs offer a higher cooling effect than single layered monocultures (Park et al., 2017). Vegetation cover may also reduce some air pollutants such as particulate matter (Diener and Mudu, 2021), whereas some species emit ozone precursors and interact with air pollutants (Knight, 2021). More research is needed to characterise the health impacts of these complex interactions, and careful consideration is needed in designing urban green spaces that maximise health benefits and minimise negative impacts (Salmond, 2016).

Policy relevance: Defra's 25 Year Environment Plan (25YEP) (Defra, 2018) is an ambitious policy to protect, restore and sustainably manage the natural environment to deliver multiple benefits for all species. The 25YEP pledges to increase urban GI in acknowledgement of the multiple health benefits associated with quality urban green spaces. The Environmental Improvement Plan 2023 builds on the 25YEP, with 'Reducing risks from heat' as 1 of 7 points in the delivery plan (Defra. Environmental Improvement Plan, 2023).Cities such as Bristol are already increasing vegetation cover to mitigate against high outdoor temperatures (Walters and Sinnett, 2021).

Measurable, specificity and scale: Satellite imagery of Normalised Difference Vegetation Index (NDVI) can give detailed high-resolution information on the level of urban greenery by measuring the difference between near-infrared (which vegetation strongly reflects) and red light (which vegetation absorbs). England's GI Mapping Database can provide a nationally consistent approach to assessing local GI provision against existing GI standards (England and Database, 2021). Some areas such as Manchester, Birmingham and Greater London also hold data on the location and size of various tree species (Greater London Authority, 2021; Factory et al., 2017; City of Trees, 2022).

Practicality and feasibility: NDVI and satellite imagery are easily accessible but processing the data requires considerable technical use of spatial analysis software. Information on tree species, size and location may not be readily available or may be costly to obtain. Cross-discipline input is needed when integrating ecological parameters (such as plant species, and canopy size) with meteorological measures (temperature, humidity, precipitation) to develop an indicator that can characterise the multi-functionality of greenspaces.

Robustness and reliability: There is currently no established indicator to systematically measure the cooling effect of urban greenspaces and the resulting health impacts. Previous studies have used temperature along a greenspace gradient to show how greenspace may mitigate heat-related mortality (Murage, 2020). More work is needed to develop an optimal indicator which could be achieved by integrating existing GI data with other datasets to understand how interactions with greenspaces translate into heat-health outcomes.

4. Discussion

4.1. Summarising the results

The projected increases in average temperatures and frequency of heatwaves (IPCC, 2021), accompanied by increasing vulnerability attributed to an ageing population (Agency and Effects, 2012), point towards a future increase in heat-related health impacts in the absence of effective adaptation (Agency and Effects, 2012). Climate resilient societies require a comprehensive intersectoral programme and policies to tackle climate risks. Health information, surveillance and climate early warning systems are core components of an integrated public health delivery. Our proposed indicator set responds to this and makes a strong case for developing a co-ordinated means of monitoring changes in population vulnerabilities and outcomes, and progress in the implementation and the effectiveness of adaptation strategies. We used a three-pronged approach of stakeholder engagement, literature review and expert opinion, and proposed ten indicators to protect population health and support action against heat-health risks. The indicators are explicitly aligned with the DPSEEA framework to ensure the measures are inter-related in a cause-and-effect chain to support: the assessment of changes in key exposures (temperature and UV radiation), the quantification of known health effects linked to the exposures (deaths and illness), the monitoring of vulnerabilities (social isolation and poor housing) that exacerbate health effects, and tracking progress on the implementation of actions that promote adaptation and improve health (community risk profiles, heatwave action plans, modifying individual behaviour or urban landscapes). An assessment (and qualitative rank) against critical indicator properties showed substantial variation in the indicators' readiness for immediate use (Fig. 1). All the indicators fulfilled the criteria of 'sensitivity to health outcomes' and demonstrated 'policy relevance', but for most, technical input and varying levels of data processing are needed to generate measures that are suitable for local area use, and that meet the required standards of robustness.

4.2. Contextualising our findings in the existing literature and practice

To our knowledge, this is the first attempt to pool together a heat-health indicator group that can be used locally to concurrently assess impacts in the context of vulnerabilities and monitor progress on adaptation to rising temperatures. Previous indicator groups such as those developed by the CCC to track progress on adaptation are broader than heat exposure, covering several climate-related risks (CCC, 2022). However, these indicators are for national (as opposed to local) application, and issues relating to gaps in data availability, accessibility and quality are cited as a major constraint across the indicators (CCC, 2023). Furthermore, there is agreement that adaptation needs are context specific in terms of varying climate change risks and vulnerability (CCC, 2023) which makes nationally derived indicators of limited relevance for local application.

A previous paper (Ebi et al., 2018) that reviewed approaches to identifying relevant climate change and health indicators generated three categories that closely match our approach; 1) indicators of health vulnerability, exposure, and risk; (2) indicators of climate change impacts on health; and (3) indicators of adaptation processes and health system resilience (Ebi et al., 2018). That study states that their criteria for indicator development was applied to the Ministry of Health in Cambodia. The paper describes the process and stakeholder engagement but does not provide any information on the resulting indicators.

In the UK, heat-related indicators are not included in local indicators such as the Public Health Outcome Framework (PHOF) (Office for Health Improvement and Disparities, xxxx). Indicators on wider determinants of health (such as information used by local areas across housing, transport, education, and other policy areas) are legitimate aspects of a public health surveillance system. However, in the UK, local areas tend to use process indicators to monitor progress toward locally agreed goals, while national agencies undertake surveillance tasks related to outcome indicators such as surveillance of diseases and mortality outcomes, which are then translated to local indicators such as PHOF (Office for Health Improvement and Disparities, xxxx). Public health surveillance is not confined to monitoring of health data in relation to emergencies, but includes monitoring of hazards and exposures that exist within the context of societal drivers and states, and actions needed to address them, as recognised within a DPSEEA approach (Hambling et al., 2011). The 'Environmental Public Health Tracking' (EPHT), which links information on environmentally related diseases, human exposures, and environmental hazards (McGeehin et al., 2004) is an example of an effective tool for integrating environmental exposure and health data. EPHT has been operationalised in public health surveillance and is recognised in many countries (Lauriola, 2020).

4.3. Strengths and weakness of the approach

Our review improves on previous work on indicator development in several ways. Firstly, the use of existing conceptual frameworks for indicator selection gives transparency and structure to the process (Niemeijer and de Groot, 2008). Secondly, applying a DPSEEA framework which is familiar to the health sphere provides a fuller picture of the links between the environmental exposure, effects on health and adaptation actions, underscored by prevailing vulnerabilities. Thirdly, we indicate the practicality and feasibility of developing the indicators that are not immediately available and provide information on possible data sources (where available). Some of the suggested indicators such as uptake of behaviour changes are particularly novel and often overlooked in the literature.

There are some general limitations to this work and where possible we discuss the specific gaps under each indicator. Some of the proposed indicators are only applicable to a UK setting such as where the data have been collected for other purposes (for example the information on community risk registers), although the development of nearly all the other indicators is replicable in other settings. The indicator set has a narrow focus on heat exposure, though our suggested approach to indicator selection can be applied across other climate change related risks.

4.4. Policy implications and future directions

Local area assessments are key to monitoring progress. Firstly, these areas are small enough to investigate geographical disparities but large enough to explore contextual drivers of variation, and to implement adequate interventions. Secondly, local governments are Category 1 Responders (Cabinet Office, 2013) and are responsible for delivering multi-sectoral local services including public health and emergency preparedness. Lastly, local government service delivery is also closely aligned with areas of potential intervention to prevent or minimise heat-related vulnerabilities and impacts, including place-based approaches that can be implemented via urban planning, landscape management and housing.

Developing these indicators will require dedicated resources or national ownership with enhanced cross-sectoral collaborations to share expertise and resources. National public health agencies are well placed with their mandate for public health protection and leadership in translating climate evidence into action. The development of the required indicators can draw on existing governance and capacity to develop, deploy, and evaluate environmental public health surveillance systems and related platforms that use public health information to support the management of environmental hazards and exposures (UKHSA, 2022). The necessary resources would be needed and could be galvanised from the delivery of the National Adaptation Programme for national public health agencies, including, for the UK, the development of the Adverse Weather and Health Plan (England, 2021) and periodic updates of the Health Effects of Climate Change UK report (Agency and Effects, 2012).

5. Conclusion

We propose ten indicators to support the goal of intersectoral collaboration towards protecting the population and supporting action against heat-health risks by; assessing changes in key exposures, quantifying health effects linked to the exposures, monitoring vulnerabilities that exacerbate the health effects, and tracking progress on the implementation of actions that increase resilience and improve health. These indicators have varying levels of readiness – they are all largely sensitive to health outcomes and have policy relevance, but to be of immediate local area use, many will require substantial resourcing in technical input and data processing.

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Credit authorship contribution statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2023.108391.

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