








Review

Beyond Climate Change and Health: Integrating Broader Environmental Change and Natural Environments for Public Health Protection and Promotion in the UK

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Abstract: Increasingly, the potential short and long-term impacts of climate change on human health and wellbeing are being demonstrated. However, other environmental change factors, particularly relating to the natural environment, need to be taken into account to understand the totality of these interactions and impacts. This paper provides an overview of ongoing research in the Health Protection Research Unit (HPRU) on Environmental Change and Health, particularly around the positive and negative effects of the natural environment on human health and well-being and primarily within a UK context. In addition to exploring the potential increasing risks to human health from water-borne and vector-borne diseases and from exposure to aeroallergens such as pollen, this paper also demonstrates the potential opportunities and co-benefits to human physical and mental health from interacting with the natural environment. The involvement of a Health and Environment Public Engagement (HEPE) group as a public forum of “critical friends” has proven useful for prioritising and exploring some of this research; such public involvement is essential to minimise public health risks and maximise the benefits which are identified from this research into environmental change and human health. Research gaps are identified and recommendations

made for future research into the risks, benefits and potential opportunities of climate and other environmental change on human and planetary health.

Keywords: demographic change; infectious diseases; vector-borne diseases; aerosolized exposures; pollen; well-being; public health; land management; patient and public involvement (PPI); land-use

1. Introduction

There is a growing awareness of how biotic (i.e., all animal and plant life) and abiotic (e.g., geological, weather and climate) natural systems interact to affect human socio-cultural-economic activities, and ultimately human and planetary ecosystem survival [1,2]. Although there has been a significant focus on how human activities both affect the climate and are affected by it, climate change is only one example of how broader patterns of environmental change are both caused by and influence human behavior and the health and well-being of global populations [3–7]. For instance, changes in land-use (e.g., increased urbanization), farming practices, industrial activities, and transportation networks, all interact with changes in climate to produce complex threats to health from both natural sources (e.g., changes in the distribution and prevalence of allergenic pollens, vector-borne diseases, and harmful algal blooms) and from anthropogenic sources (e.g., persistent organic pollutants, heavy metals, and an over-abundance of nutrients in surface waters) [3–5,8].

At the same time, there is an increasing evidence base and appreciation of the potential benefits of natural environments for human health and well-being [9,10]. Humans have actively destroyed, degraded, and impacted natural environments for millennia, yet increasingly the potential and realized value of these environments as ‘natural capital’ (especially natural environments that are of high quality and/or well managed), are being noted economically and culturally [11]. Thus, environmental change does not necessarily need to be bad. Good management, underpinned by state-of-the-art science, might actually be able to promote and support health and well-being, with evidence suggesting that the benefits may be strongest for some of the most vulnerable in society who are often the most exposed to environmental threats [12,13]. Ultimately, these insights can inform significant international efforts at producing sustainable, as opposed to unsustainable, growth (e.g., UN Sustainable Development Goals (SDGs), <https://sustainabledevelopment.un.org>) [9,14–16].

The aim of the current paper is twofold. First, it summarises and uses as exemplars selected research from a six-year cross-sector multi-centre UK funded initiative, the National Institute of Health Research (NIHR) Health Protection Research Unit (HPRU) in Environmental Change and Health (<http://www.hpru-ech.nihr.ac.uk>). The initiative was explicitly developed to improve our understanding of these complex interactions between different types of environmental change and human health. The HPRU project as a whole examines health in the UK within, and across, three core themes: Climate Resilience (Theme 1), Healthy and Sustainable Cities (Theme 2), and the Natural Environment (Theme 3); the focus of the current paper is Theme 3. “Natural environment” in this UK context includes all nature which has been impacted on by anthropogenic influences, across the urban and rural landscapes. Topics examined in this paper include a range of risks and threats to health, such as changes in the distributions of allergenic pollens and vector-borne diseases under a changing climate and other environmental change, as well as opportunities for health promotion through changes in the salutogenic use of green and blue spaces (e.g., for physical activity and/or well-being enhancement).

The second aim of the current paper is to draw these various strands together. In particular, the paper presents how an integrated understanding of the complex and multi-faceted interconnections between humans and their environment, including an improved understanding of how to balance the risks and benefits, is needed to identify and support opportunities to develop practical solutions able to protect and promote public health in a changing environment. And as a corollary (as we discuss

below), essential to this area of research going forward is the integration of community involvement throughout the research process in identifying and understanding the impacts of environmental change on human health and well-being. This section builds on: (a) the growing awareness of the interconnections between the health of both the environment and humans in the medical, public health, environmental, and economic sciences, the arts and humanities, and among diverse communities including government, business, non-governmental organizations (NGOs), and communities; and (b) new perspectives and conceptual frameworks attempting to understand and articulate these ideas such as: One Health, Planetary Health and Planetary Boundaries, Environmental Global Health, Evolutionary Health, the Overview, EcoHealth, and Ecologic Public Health, as well as more general calls for 'systems thinking' [17,18].

The research we summarize and illustrate from the HPRU in Environmental Change and Health extends from earlier work by using a more systematic approach to integrate climate and other environmental change within a single interdisciplinary research programme. Additionally, the paper attempts to: indicate the global relevance and interconnections beyond the UK; identify areas of knowledge and research gaps; and stress the need for continuous assessment and monitoring of the risks and benefits of ongoing environmental change on the interactions between humans and the natural environment for their mutual health and future existence.

2. Background

Climate change is a major future (and increasingly current) threat to the health of humans and the planet. There are many ways in which climate change can impact human health and well-being through the natural environment, including more frequent and intense extreme weather events (e.g., hurricanes/cyclones), temperature changes, sea level rise, etc. (Table 1). Although accepted for several decades in the wider environmental science community, research into these effects of climate change on human health are relatively recent [3–5], but growing [18–21]. There is also increasing recognition that climate change effects that may appear to be distal in time and/or space can still have major effects on ecosystems and human health in areas such as the UK in the present or near future [22].

These climate change factors and effects cannot be viewed in isolation, nor as the sole drivers of effects on the natural environment or on current and future impacts on ecosystem and human health. In particular, other types of environmental change, ranging from natural and manmade contamination/pollution to changes in land-use need to be factored into any consideration of the effects of climate change on human and environment health (Table 1 and Figure 1). These other examples of environmental changes illustrate how humans (and their attempts to adapt to and mitigate these changes) currently affect the "health" of the natural environment, and how this can have ongoing (often unintended) consequences by impacting on current and future health and well-being.

An example of this is the contamination of the natural environment with manmade pharmaceuticals. For instance, antibiotics have been over-used in both human and veterinary healthcare, leading to the phenomenon of antimicrobial resistance (AMR), considered to be as big a threat as climate change to the future of humankind [23,24]. When AMR was initially described, it was identified as originating in hospitals, and then spreading into the community. However, due to ongoing antibiotic contamination of the natural environment, together with normal evolutionary processes, AMR is now developing widely in the natural environment and the community, and then entering back into hospital environments with potentially extremely serious direct consequences for human and animal health [24].

An especially challenging concept for the public health and research community is that of social complexity in the determinants of health and well-being. In the "socio-ecological model of health", health and disease are viewed as products of a complex interaction between societal-level factors (e.g., the physical environment) and characteristics specific to the individual (e.g., individual behavior). Although it is a recasting of much older ideas, this socio-ecological model transformed what was often a very siloed public health world at the end of the 20th century. Furthermore, acceptance of this model is especially challenging because it demands recognition of a much more complex real-world and policy

context for research and action in environment and human health. Many of the highest profile public health challenges (e.g., mental health issues, well-being, and increasing inequalities) are recognized as being driven by multiple interacting determinants, including the natural environment [25].

Table 1. Climate and other environmental changes with potential for large scale population health impacts, highlighting contextual, adapting, and mitigating factors.

Climate Change Factors	Other Environmental Change Factors	Other Context Factors	Possible Mitigating/Adapting Factors
<ul style="list-style-type: none"> Variable weather with temperature extremes Extreme weather events Sea level rise Ocean acidification 	<ul style="list-style-type: none"> Decreasing planetary resources (e.g., phosphorus, “rare earths” used in electronics, fossil fuels) Land-use changes Decreasing biodiversity Loss of species and habitats Anthropogenic Pollution (POPs, nutrients, pharmaceuticals, plastics, nano particles) Decreasing availability of potable water Continuing emissions of air pollutants from combustion Invasive species (including vectors for disease) Continuing emissions of nutrients and increasing harmful algal bloom risk Changes in planting patterns (and associated pollen risks) 	<ul style="list-style-type: none"> Human demographic change (older, living longer, growing population) Increasing chronic diseases (physical and mental) in human populations Increasing inequalities within and between countries Increasing migration Increasing international trade in food Increasing Tourism Increasing international transport Chronic conflicts 	<ul style="list-style-type: none"> Increasing use of renewable energy Increasing Internet/Globalized communication Increasing access to Big Data Increasing education of women/girls Increasing community co-creation/participation Pro-environmental behavior (e.g., recycling, active travel) Technology Increasingly taking climate and other environmental change into account in international finance, policy and governmental planning (e.g., Paris Accords)

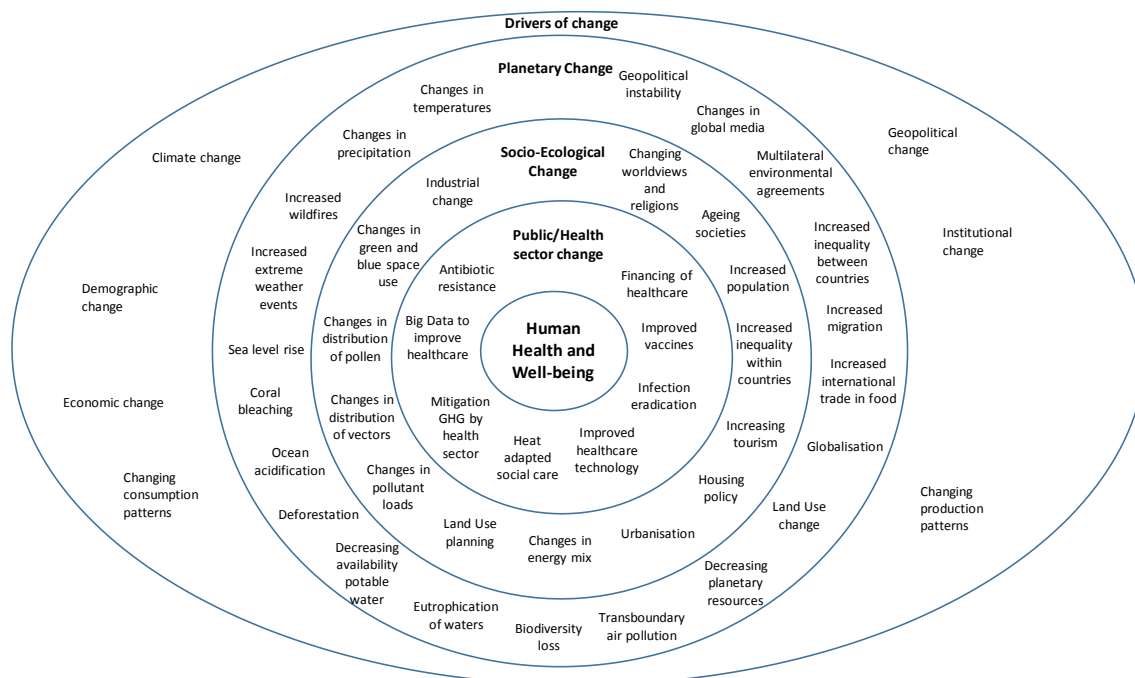


Figure 1. Environmental Change and Health: Global, Socio-ecological and Public/Health Sector changes that impact on human health and well-being.

In particular, theory and research on environment and human health from the public health community have been limited by thinking and perspectives which have focused on the health of only human populations, to the exclusion of the health of the natural environment and other organisms, including a lack of appreciation of the impacts of ecosystem “health” on human health and well-being and resilience [15,16]. More recently, the evolution of thinking in this area has been dominated by a wider understanding of the health, equity and existential relevance of the exceedance of “planetary boundaries” for both ecosystems and humans [26,27]. This development requires both the environment and health research communities to think and act together on vastly extended temporal and spatial scales, and to embrace further layers of complexity in analyses and investigation [25].

Ultimately, the result of the complex interactions (both known and unknown) of climate and other environmental change with all the other factors mentioned above impacting on ecosystem and human health, will determine all of our “Planetary Health” [27]. The consequences of some of these drivers on environmental change are discussed briefly below, particularly in the context of other factors which may lead to both risks and benefits for humans and the natural environment. As stated above, ongoing research from the Natural Environment Theme of the HPRU in Environmental Change and Health is used as exemplars below.

3. Climate and Other Environmental Changes, and Infectious Disease Risk

There are many historic examples of changing weather patterns and their impacts on the health of the humans and ecosystems of historic civilisations [28]. All sorts of drivers can affect infectious diseases [29], and most known and emerging infectious disease outbreaks are not directly attributable to changes in weather/climate. From the perspective of responding to emergencies, there are recent international examples of unexpected events that have initiated outbreaks including post-disaster outbreaks of cholera, and emerging infectious diseases such as Ebola and Zika. In these examples, a change in climate was not an important factor directly contributing to the increased cases, but they do illustrate the difficulties of predicting and managing such events. However, because some historic events have been associated with sudden changes in the burden of infectious diseases, it seems reasonable to be prepared for what might change in the coming years to better understand the weather and other drivers, and how these can influence the behaviour of individual pathogens. Globally, the historic overview suggests those most likely to be affected will be the poor rather than the rich, and those in low-income, rather than high-income countries.

3.1. Water-Borne Infectious Disease Risk

A variety of techniques have been used to examine the association between weather and various infectious diseases [30,31]. Water-borne infectious disease outbreaks have been associated with climate/weather, such as sporadic cryptosporidiosis [32,33]. A systematic review examined 24 papers on outbreaks of water-borne infectious disease and found associated factors included low rainfall, increasing temperature and heavy rainfall before the outbreak [34]. The impact of weather on drinking water quality is reduced with the provision of modern drinking water supplies, but is more marked in private water supplies [35]. Although modern treatment should still be able to cope with most extreme weather events, drinking water quality and supply may come under increased pressure with changes in climate. Flooding can impact on the infrastructure of water treatment, sewage disposal, and electricity supply. In the Baltic and beyond, seawater temperature may also be playing a role in the increase in diseases such as cholera related to the bacteria, *Vibrio* spp. [36].

The supply of food may be adversely influenced by drought or floods affecting agriculture [37,38]. As part of the HPRU in Environmental Change and Health Theme 1 research, we have explored the health and well-being consequences of flood exposures in the UK [39] and found that the seasonality of a number of foodborne pathogens can be influenced by weather, particularly temperature [40]. We have also reviewed the seasonality of over 2000 distinct infectious diseases reported in the UK [41] and the co-occurrence of weather conditions with human infection cases of individual pathogens provides

some indication that these might be related. However, because such links can be associated with a range of other variables, we have developed techniques that link local weather to individual patients so that the weather components can be partly decoupled from seasonality; methods for extracting and linking these data locally have also been tested, based on linking the geographical location of where diagnosis data were collected and analyzed, with weather data for that location [42].

One of the problems with linking human infections with the weather across large areas is the differences in monitoring (including methods, reporting and completeness), particularly over a sufficiently long timescale [43]. To facilitate a wider analysis of pathogens, we have also reviewed methods used in linking water-associated diseases with climate [30,31], developed methods based on the infectious disease *Campylobacter* as a case-study (see Box 1), and produced a website for visualising data and generating hypotheses about the relationships between weather parameters and disease (<https://www.data-mashup.org.uk/research-projects/climate-weather-infectious-diseases/>).

Box 1. *Campylobacter* Case Study.

Campylobacter represents a good case example of an organism to study the effects of climate and weather on human infections in the UK and beyond. This is because the organism has a seasonality which is different from all other pathogens [44], numerous previous studies have been unable to identify the driving factors for this seasonal distribution [45–48], and since chickens appear to be an important source of infection, the association with weather is likely to be multi-factorial and indirect.

Within the Health Protection Research Unit (HPRU) in Environmental Change and Health research, the comparison of data based on the weekly incidence of campylobacter infections in the UK at different temperature and rainfall values has been useful in partially separating out the weather component from seasonality [49,50]. One traditional way of examining a time-series analysis is to use an autoregressive integrated moving average (ARIMA) model, and this has been adapted to include seasonality (SARIMA). A range of methods have been used to examine these, including: a novel Comparative Conditional Incidence (CCI) wavelet analysis [51]; hierarchical clustering [52]; generalized additive models for location, scale and shape (GAMLSS); and generalized structural time series (GEST) models [49,50]. This area of work is going to be further developed by future HPRU research so that it can be applied to a wider range of pathogens, weather/climate change and other complex factors.

3.2. Vector-Borne Disease Risk

The status of vector-borne diseases (i.e., infections transmitted by arthropod vectors) has changed significantly in the UK and Europe over the early 21st century [53]. During the early 20th century outbreaks of dengue and malaria were common in the Mediterranean region. Both malaria and the dengue mosquito vector, *Aedes aegypti*, were largely eradicated later that century so interest in vector-borne disease in Europe waned. However, the discovery in the early 1980s that the bacteria, *Borrelia burgdorferi*, in *Ixodid* ticks, which causes Lyme borreliosis (i.e., ‘Lyme disease’), increasingly raised concerns over the role of ticks as disease vectors in Europe. Ticks are also known to be efficient vectors diseases, including the tick-borne encephalitis virus, the Crimean-Congo Haemorrhagic fever virus (rickettsial bacterial infection,) and other pathogens such as *Babesia*, *Anaplasma*, *Neoehrlichia*, and Louping Ill (infectious encephalomyelitis of sheep).

In 2012, dengue fever returned to Europe with >2000 cases in Madeira [54], and each year there are local cases of either dengue and/or chikungunya viruses across the Mediterranean Basin, including >400 cases of chikungunya in Italy in 2017 [55]. This transmission is associated with the importation, establishment, and spread of non-native invasive mosquitoes, *Aedes aegypti* and *Aedes albopictus* [56]. Since the start of the 21st century, West Nile virus has also consistently been reported in Eastern and Southern Europe, and more recently there have been local outbreaks of malaria in Greece and Italy [57]. The large outbreak of Zika virus in the Americas in 2015–2016 has further highlighted the threat posed by imported non-native mosquitoes and the potential for continental and global spread of mosquito-borne arboviruses, thus ensuring that vector-borne diseases will be an ever present public and veterinary health issue in coming years.

The changing status of vector-borne disease risk in the UK and Europe is partly attributable to globalisation and climate change; however, there are also various other environmental change factors that could equally be playing a role, and over a much shorter timescale. The invasive *Aedes* mosquito vectors of dengue, chikungunya and Zika are peri-domestic species, exploiting containers provided by humans, and dispersing in vehicles along highway systems. Thus, they are responsive to water storage and drought, and extreme precipitation, as well as changes in climate that can impact their development and capacity as vectors. In contrast, the habitat suitability of native mosquitoes and of native and non-native ticks are also driven by habitat availability and connectivity, and animal movements, which can be impacted by environmental change [53].

In the UK context in particular, the HPRU in Environmental Change and Health has focused on the sheep/deer tick, *Ixodes ricinus*, as the primary vector of Lyme borreliosis. It is able to feed on a variety of animal hosts during its three active life stages: larva, nymph and adult. This non-specialist feeding behaviour means that they can feed equally on wildlife, companion animals, livestock and humans, depending upon availability. These ticks thrive in the moist mild UK climate; however, their ability to survive off host is primarily determined by habitat structure, as well as animal diversity. Whilst historically it is a tick of upland sheep pasture and lowland woodland, these ticks are now found in lowland grazed grassland and urban green-space. Their dispersal throughout the countryside is contingent on their movement by animals.

It follows therefore that any environmental management of habitats that increase habitat connectivity or coverage, leads to greater dispersal and greater abundance of ticks. Recent published surveillance data by Public Health England (PHE) reported a significant change in the distribution of *Ixodes ricinus* [58], with particular expansion in the southern UK counties. Habitat management that favours ride (path) management in woodland, the creation of field margins, the impact of increased ecotonal habitat (i.e., habitat between two distinct habitats), changes in management of grassland habitat, or urban greenspace, have all been shown to influence the survival and abundance of ticks. In turn, the prevalence of the *Borrelia* bacteria within ticks is also influenced by both habitat and animal diversity [59–61].

This complex interplay between habitat, climate, animal population dynamics, vector density and pathogen prevalence demonstrates remarkable spatial and temporal heterogeneity, even at fine spatial scales. Although any scheme that modifies and enhances habitat structure may impact tick abundance in the UK, there are opportunities for managing these habitats to both maximise biodiversity and minimise human exposure and public health impacts [60], which can be particularly challenging in an urban setting (see Box 2). Further studies to develop empirical data both to inform such interventions and to understand the ecological aspects of disease transmission cycle are now a priority.

Box 2. Urban greenspace and ticks in the city of Bath (UK).

Urban greenspace has been linked to improved human health and well-being, and such spaces are a focal point of the UK government adaptation plans to mitigate the effects of our changing climate. The benefits of urban greenspace and the arguments for increasing and improving access are clear (as discussed later in this paper), but it is important to also investigate the potential risks posed by tick-borne disease. To date, few studies on ticks in urban greenspace have been conducted in the UK. This research aimed to fill these gaps, and helps inform guidance development. Methodology involves identifying a range of urban greenspace habitats such as woodland, woodland edge, meadows, parkland and short grassland. In each habitat and at each site, standard tick collection is conducted using flagging a cloth over vegetation. Ticks are counted and identified, with abundance of ticks calculated for unit area. All ticks are tested for *Borrelia* bacteria using PCR and sequenced to genospecies to inform Lyme risk. Following initial surveys in Salisbury (UK) on the suitability of urban greenspace for ticks and the *Borrelia* bacteria (causing Lyme disease), comparable surveys were commenced in the city of Bath, working closely with Bath and North East Somerset (BANES) local authority. BANES have a network of natural and managed urban greenspace, and this involves the creation of urban meadows. BANES have also led the way in working with Public Health England (PHE) with regard to assessing and mitigating the risks posed by urban ticks. Integrating the findings of academic and public health research on tick and Lyme risk enables better informed assessment of risk and appropriate public health awareness strategies, and this is proving a model that needs to be replicated across local authorities in the UK where urban ticks are being reported.

As part of the HPRU, field sampling of urban greenspace in Bath has taken place over the last two years, and found high suitability for ticks in some areas, mainly in woodland and woodland edge habitat, and the presence of *Borrelia*-infected ticks. So far, based upon preliminary results, prevalence rates appear lower (at 4.5%; unpublished data) than Salisbury (18.1%) [61], and appear restricted to only parts of the city. This work has been integral to enabling BANES to provide accurate tick awareness material, target their interventions, and assess the risks posed to humans by ticks and the impacts of their management. However further evidence is required, and as part of the HPRU in Environment and Human Health research, further sampling is taking place in Bath as well as in other cities such as Bristol and Southampton. Based upon this collective field research, PHE will be in a better position to advise local authorities, and to begin developing guidelines that can be used for management and in targeting tick awareness.

In contrast to tick-borne disease, which currently causes 2000–3000 cases of human Lyme borreliosis each year, the disease threat posed by native UK mosquitoes is currently insignificant; however, this should not lead to complacency. The incidence of several arbovirus diseases in the rest of Europe, together with the facts that malaria was once endemic in the UK and that mosquitoes are still a serious pest in some localities, suggest there is a need to understand how climate and other environmental change might affect future disease risk.

For example, in the UK, there is a large-scale programme for the development of new wetlands. The aims of this programme include: the managed re-alignment of the coasts to create new saltmarsh and mudflat habitat to mitigate coastal flooding and storm surges, as well as creating new protected habitats; the reversion of arable land to flooded grassland, as part of large-scale wetland expansion projects; and the creation of urban wetlands to provide sustainable urban drainage and to create mitigation habitat under the European Habitats Directive [62]. Field studies in the UK in each of these habitats has shown that mosquitoes do exploit newly created habitats, but their ability to colonise is largely dependent upon the design of new wetlands, the management of tidal waters, the flooding regime of wet grassland and the design of ditches, scrapes and sewage treatment reed beds [63–65]. The UK has 36 recorded species of mosquito, three of which have only been detected in the last 5–10 years [66] and one is known to be non-native and very invasive [67].

Although there is no current health risk, a warming climate and changes in animal movement and human interactions with the natural environment, coupled with an increase in the numbers of infected travelling pets, mean that any habitat management strategy that favours mosquito habitat could be significant. As with ticks, research that focusses on the how these vectors may be managed within the environment, particularly in protected habitats, is a key requirement for future contingency planning. Ensuring that we can progress environmental change and increase biodiversity, without the

unexpected negative impact on vector-borne disease risk, is a priority area for PHE and the HPRU in Environmental Change and Health.

4. Aeroallergens/Aerosols Risk: The Case of Pollen

Aeroallergens contribute to the increasing burdens of asthma and allergies on society. The financial costs associated with asthma (excluding wider societal costs) in the UK have been estimated at £1.1 billion per year [68]. Seasonal allergies including allergic rhinitis ('hay fever') have been increasing in the UK, with some reports suggesting that as many as 40% of UK children suffer from hay fever [69]. Recent results from the "Britain Breathing" project, show that self-reported seasonal allergy symptoms across the UK are strongly correlated with reduced well-being, and these trends also correlate with the number of antihistamines prescribed by general practitioners [70].

Pollen from certain plant taxa or species, particularly grasses and some tree species (e.g., Betulaceae (birch)), can exacerbate allergenic conditions, including hay fever [71,72] and asthma [73,74]. Although the scale of individual sensitivity is highly variable, it is associated with exposure to pollen grains and the allergenicity of the pollen. Therefore, to help understand and manage individual exposure to allergenic pollen, it is important to: (a) quantify the health impacts of short-term increases in pollen exposure; (b) know where the major concentrations of allergenic plant species are located; and (c) forecast with reasonable accuracy, the timing, amount and dispersion characteristics of pollen emissions. Climate change is likely to affect pollen exposure through changes in plant productivity, the geographical range of allergenic species, the amount and allergenicity of pollen produced by each plant, and the timing and duration of the pollen season [75]. At the same time, there are ongoing efforts to increase the amount of and access to green space in urban areas to promote physical and mental well-being, which may result in increasing human exposure to mixtures of pollen with air pollutants (as discussed below).

There is the potential for research to inform planting, land management and development practices in order to reduce allergy risk [76]. For example, there is currently a widespread preference for planting only male trees along roadsides to avoid street litter from seeds and fruit produced by female trees. However, this can increase allergenic pollen exposure due to the pollen produced by the male trees. Tree planting might also be promoted to mitigate allergic exacerbation in urban areas where co-exposure to air pollutants is high. Grass cutting regimes can be modified to cut grass before it flowers and produces pollen.

The exacerbation of allergic respiratory conditions from pollen exposure may be intensified by air pollutants. Laboratory and field experiments suggest that air pollution and allergenic pollen exposures may interact [77]. For example, studies show that ozone [78,79] and nitrogen dioxide [80,81] can affect pollen morphology and change the pollen protein content or protein release processes, thus increasing the risk of allergic reaction following inhalation, with effects being species and concentration dependent [82]. Furthermore, grass pollen can attach to particulate air pollution (e.g., diesel exhaust particles), allowing allergenic particles of combined pollen and air pollutants to become concentrated in polluted air [83].

To address this research gap, studies conducted by the HPRU in Environmental Change and Health have focused on mapping the location of allergenic plant species across the UK [84] and relating pollen and land cover with health outcomes, including asthma exacerbation-related hospital admissions [85]. Results of this latter study showed that daily concentrations of grass pollen were significantly associated with adult hospital admissions for asthma in London, with a 4–5 day lag from increased pollen levels to hospital admissions. Increased hospital admissions were also associated with grass pollen concentrations categorized using the Met Office's 'pollen alert' levels, which range from 'very high' to 'low' days, with a lag in this case of three days. Additional research has examined the complex relationship between air pollution, land-use/cover and human health (see Box 3).

Box 3. Aero-allergens, land-cover and asthma.

Relationships between vegetative land cover and respiratory conditions are potentially influenced by multiple causal pathways. For example, whilst the presence of trees may increase local risk through their emission of allergenic pollen, those same trees may reduce local air pollutant concentrations [86,87] which also exacerbate conditions such as asthma [88,89]. In a similar way, areas of greenspace may result in localised seasonal exacerbation due to grass pollen emissions, but may also contribute to the reduction of asthma risk factors (e.g., obesity and stress) by providing a setting which promotes exercise and psychological restoration.

In recognition of both the effects of multiple and apparently opposing pathways, and also the potential interaction between pollutant and pollen exposures, another strand to the HPRU in Environmental Change and Health research has aimed to clarify the net effects of residential area exposure to trees and greenspace at different levels of background air pollutant exposure [90]. A comparison of UK asthma hospitalisation rates across 26,000 small urban areas showed that trees were associated with greater reductions in asthma hospitalisations when air pollutant levels were higher, but had no effect when air pollutant levels were very low; whereas greenspace was associated with greater reductions in hospitalisation when air pollutant levels were lower, but had no effect when air pollutant levels were very high.

Further work is underway to understand and model the environmental determinants of the key allergenic species or taxa across the UK. This will enable prediction of their spatial ranges, timing of pollen emissions, and concentration of pollen grains of the different species/taxa in the atmosphere at any time and location across the UK (both in the current climate, and under future climate and other environmental change scenarios).

5. Benefits of Natural Environments

As noted above, there is a growing recognition that the sustainable management of the world's natural resources is vital for human health, well-being and resilience, often referred to as 'Natural Capital' or 'ecosystem services'. Even at a very basic level, the air we breathe, the water we drink, the food we eat, and the sources of energy we rely on all depend on natural processes that support and regulate the environmental systems that support all life on the planet [2,91,92]. Given the extensive literature available on the direct and indirect benefits of natural ecosystems for human health and well-being (e.g., food, water, fuel etc.), the HPRU in Environmental Change and Health has focused on researching the potential benefits from natural environments in relation to two of the most pressing current public health issues poor mental health [93] and the lack of physical activity [94]. In particular, the aim has been to explore whether the availability and utilization of 'natural' spaces for recreation could: (a) help mitigate the increasing pressures of modern living on people's cognitive and emotional health; and (b) encourage individuals to engage in levels of physical activity conducive to good physical and mental health in an increasingly sedentary society.

With respect to mental health, the aim was to go beyond typical analyses to explore how different kinds of natural setting might influence different kinds of mental health outcome. Traditionally, research in this area has demonstrated that living within a neighbourhood with more generic 'greenspace' (e.g., as measured using satellite images) is associated with a lower risk of common mental health problems such as anxiety and depression [13,95–99]. The focus has been in exploring the following areas: (a) different types of greenspace in urban areas (e.g., street trees [10,100]); (b) greenspace land cover in rural areas (e.g., managed grasslands, deciduous woodlands, moorland, [101]); and (c) well-being outcomes in relation to different exposure types (e.g., evaluative, eudaimonic (i.e., feelings of meaning and achievement), and experiential well-being [102]). In Theme 2 of the HPRU, we have also quantified the effects of urban infrastructure on local urban temperatures compared the potential co-benefits with temperatures in green environments and quantified the related health impacts [103], as well as the impact of factors such as the deprivation status of people in relation to exposure to the highest urban temperatures [104].

With respect to urban street trees, an ecological analysis controlling for indices of area level greenspace, income, deprivation, and smoking rates, showed that London boroughs with higher densities of street trees had lower anti-depressant prescription rates ([100]; see [105] for similar findings in the US). A review of the urban tree literature reported a range of other potential benefits to health, such as reduced particulate air pollution, plus some challenges such as increased exposure to

pollen [10]. Alcock et al. [101] used 18 years of longitudinal data to model symptoms of anxiety and depression using the General Health Questionnaire (GHQ) (a screening device for identifying minor psychiatric disorders in the general population) among individuals who moved between rural areas with different land cover mixes. Results suggested that the mental health of rural dwellers was better during the years when they lived in areas with a higher proportion of managed grasslands, uplands, and coastal habitats, relative to land cover associated with buildings and infrastructure. For other land cover types that might have been expected to have similar benefits (such as deciduous woodland), no such benefits were found, although some benefits have been reported in the US [106].

This research has gone beyond simply identifying (reduced) symptoms of common mental health disorders, to better understand the potential benefits to mental health and well-being from interacting with natural environments. International coordination efforts [107] have identified four key types of well-being: (a) positive and (b) negative, experiential well-being (i.e., emotions and moods); (c) evaluative well-being (i.e., global life satisfaction); and (d) eudaimonic well-being (i.e., feelings of meaning and achievement). Controlling for a range of potential confounders, the study found that the difference in levels of eudaimonic well-being between individuals who visited natural environments for recreation at least once a week, compared to those who rarely visited, was similar to the difference between individuals who were in a long-term relationship vs. those who were single/divorced or widowed. In other words, the findings raised the possibility that spending time in nature can promote the kinds of well-being normally associated with close personal relationships. Results also suggest that daily emotional states can be greatly improved by even relatively short visits to different kinds of natural settings.

In terms of physical activity, the focus of the research has moved beyond the traditional approach of demonstrating that people who lived in 'greener areas' tended to engage in higher levels of physical activity [108–111]. First, given the previous interest in the relationships between coastal and other 'blue space' environments and health [12,111–113], the research began by investigating whether individuals who lived nearer the coast in England, were also more likely to meet recommended levels of physical activity. Although there was strong support for this hypothesis in the West of the country, including both South and North West regions, there was no support in Eastern coastal regions [114]. Possible factors may have included differences in coastal types, access, populations and weather. In order to try and control for these factors, a repeat cross-over experimental lab-based study was conducted where individuals used a stationary exercise bike while viewing a large video projection of either coastal, rural, urban, or neutral gym settings [115]. Findings suggested individuals enjoyed their ride in the coastal setting more than the other settings, were more willing to do the coastal ride again, and importantly, had different perceptions of the passing of time in the coastal setting, suggesting that they might be willing to exercise for longer periods by the sea, with associated benefits to health (Box 4).

Box 4. Natural environments: the Monitor of Engagement with the Natural Environment (MENE) survey.

The HPRU in Environmental Change and Health research examining the potential health and well-being benefits of interacting with the natural environment has used a range of methods and datasets to explore the factors which may be related to the use of natural environments for physical activity. Several studies have used the Monitor of Engagement with the Natural Environment (MENE) survey of how people use the natural environment in England which has collected data on over 40,000 individuals per year since 2009. For instance, using data from over 280,000 individuals we estimated that the total amount of physical activity conducted in all natural environments in England had a social value of over £2 billion per year, in terms of Quality Adjusted Life Years (QALYs) [116]. A second study suggested that while local greenspace is positively associated with increased levels of physical activity among dog owners, there is no relationship with non-dog owners [117].

Additional research using the MENE dataset has identified the key reasons people report for rarely or never visiting natural environments for recreation, and the factors predicting those reasons [118]. For instance, nearly 20% of infrequent visitors stated that they were 'not interested' or had 'no particular reason' for not visiting these sites more often, and an analysis of the socio-demographic profiles of these individuals allowed the identification of a predominantly younger urban cohort from lower socio-economic status backgrounds who were more likely to report these reasons. Further experimental work within the HPRU suggests that this subpopulation might be an audience for interventions to raise interest or awareness in the possibility of using natural environments for health promotion in the future [119].

6. Public Involvement

An important lesson learned in this Environmental Change and Health HPRU, and of relevance to all other public health research, is the value of involving communities and other stakeholders in the exploration and co-creation of the research. Minimally, this engagement will broaden the scope of the research inquiry to include perspectives of those who are directly affected by climate and other environmental change impacts. In addition to asking different questions and instilling greater creativity, such co-creation and involvement can make the research more directly impactful and applicable to the affected communities. Furthermore, involving communities would be highly beneficial to some areas of science traditionally perceived as "less suitable" for the involvement of communities, such as mathematical modelling. For instance, insights from the communities can be crucial to the model assumptions, formulation and critical scrutiny of model findings [120,121]. There are also direct benefits in terms of training and research support by these communities (Box 5).

Public participation frequently features in strategies for addressing inequalities and enabling communities to improve health outcomes [123]. It has also been argued that addressing complex interactions between natural environments and human behaviour requires a social learning approach which goes beyond the provision of information, public consultation and community participation, to the development of 'situated and collective engagement' [8,124]. This approach speaks to what Jasanoff [125] described as the development of 'civic epistemology', the collective evaluation of knowledge to inform public policy and social action.

Yet there are a number of barriers to effective public involvement in public health research such as the HPRU which can be difficult for individual researchers or small teams to address [126]. The competences needed for effective involvement by academics and other researchers are still rarely taught as part of the research curriculum [127]. Structural support for public involvement from universities, funders and public bodies (e.g., www.ecehh.org/about-us/engagement/; www.invo.org.uk/; the PHE People's Panel) can help address barriers, but if time and resources for involvement are not integrated into research programmes from the outset, it can be difficult for researchers to access this support. Better integration of public involvement in all our research into environmental change and human health remains both a challenge and an opportunity.

Box 5. Health and Environment Public Engagement.

The Health and Environment Public Engagement (HEPE) group is a public forum of “critical friends” who have worked with the European Centre for the Environment and Human Health since 2013 (www.ecehh.org/about-us/engagement/; [122]). At quarterly meetings, HEPE discuss projects taking place in the Centre, including the HPRU in Environmental Change and Health research and support annual public workshops with researchers. These meetings use a range of participatory techniques to support inclusive and focused discussions.

The first workshop focused on prioritising issues the researchers focusing on possible salutogenic interactions with natural environments could address by linking large data sets. Researchers ‘pitched’ their ideas, and there was an initial individual vote by all workshop participants. Discussion of these choices was followed by a second vote which prioritised Mental Health and Social Relations. Notes from discussions showed some topics gained few votes because they were seen as integral to all the research rather than as individual projects (e.g., economic costs and benefits); this is a good example of why it is important to have multiple ways of recording workshop activities.

The second workshop used scenarios about individuals accessing natural environments. The group discussed whether this access made an important difference to the individuals and would any difference change their responses to self-reported health questionnaires widely used in the large secondary “big data” analysed by the HPRU team. The researchers were impressed by the magnified importance very small differences may have for people with multiple physical or mental health and social problems when answering these types of questionnaires.

The third workshop again used a scenario, this time alongside survey questions on partner/spouse relationships. Discussions explored which were most relevant as measures of social relations, and whether these could plausibly be used to help explore whether natural environments improve health directly, or whether this occurs through the promotion of better inter-personal relationships. The group members were concerned that some of the standard questions used in research in this area might introduce bias because of different cultural expectations and different interpretations of the survey questions. This insight helped the researchers to identify which data to use in the secondary data analyses for the HPRU research.

Involving the public has substantially helped to shape the European Centre’s work within the HPRU. Having HEPE as a standing group has greatly facilitated that public involvement. Public interest in this HPRU research has also attracted five new members to HEPE, with several members participated in the most recent Annual Meeting of the HPRU in Environmental Change and Health, creating a cycle of mutual interest and support.

There is a growing variety of methods and approaches for working with communities in research collaboration. For example, one method which can directly involve communities and other stakeholders is the *ecosystems-enriched Drivers, Pressures, State, Exposure, Effects, Actions* or ‘eDPSEEA’ model [128]. The eDPSEEA model can also help to populate and expand our understanding of a theoretical model of the research question which takes into account the health of both the environment and humans by integrating ecosystem services into the theoretical model, whereas the more traditional DPSEEA model has focused more on a unidirectional link between environment and human health. There are many other approaches which can engage communities and lead to improved co-creation of research and training, many of which emphasise the importance of trying to appreciate and understand the complex systems underlying interactions between human health, climate and other environmental change [17]. These are essential activities as we face a world in which human-driven actions, both intentional and unintentional, can have planetary impacts.

7. Discussion

In this paper, we have provided a brief overview of the growing subject area of human health and well-being with reference not just to climate change, but to other broader patterns of environmental change. There is growing evidence that environmental change is both caused by and influences human behavior and the health and well-being of global populations. In particular, we identified the emerging knowledge gaps in this area which are the focus of research by the HPRU in Environmental Change and Health and others [6,7]. However, there was no intention to imply that this selection of topics encompasses the entire research area of environmental change and health; rather the ongoing HPRU research provides a range of examples to demonstrate the complexity and importance of this growing research area. In this paper, we have highlighted the research on various aspects of human health

and well-being, environmental change and the 'natural environment', including both threats and opportunities that rural and managed urban natural spaces have for a range of health and well-being outcomes. A key focus of the research has been on how a true appreciation of the complex and multi-dimensional nature of environmental change and health requires a deep integration of research approaches and findings from often disparate perspectives (including active community involvement), in order to better inform the trade-offs needed at a public health policy level.

The experience of the UK with regards to the impacts on the health of both humans and the natural environment from climate and other environmental change is not unique. As noted above, it is important to broaden our view of the potential effects of climate and other environmental change to include phenomena taking place distant in time and/or space from the UK (i.e., a more planetary perspective). Furthermore, the research presented in this paper demonstrates that there are lessons to share and to learn from others, particularly with the most vulnerable populations likely to be affected by climate and other environmental change, such as the tropical developing world, island states, and the polar regions, as well as our more local communities.

If we compare the achievements reviewed in this paper with research agendas such as those promoted by the World Health Organization (WHO) and other international agencies, the task has only barely been outlined by work conducted so far [5,6,129–131]. The assessment of health risks attributable to climate and other environmental change has only just started, including some initial evaluation of indirect effects such as infectious diseases. However, more remains to be done in terms of the assessment of effectiveness and cost-effectiveness of health protection and promotion strategies and measures, the assessment of the health impacts of potential adaptation and mitigation measures, and the assessment of the likely financial costs necessary to protect public health from climate and other environmental changes.

The main research gaps can be categorized as outlined below. There is a need to undertake research to:

- identify the most effective interventions, by systematic reviews of the evidence base for interventions, and/or by using methodological research to improve analytical tools for analysis of cost-effectiveness;
- identify the health co-benefits of mitigation and adaptation actions to address climate and other environmental change in non-health sectors. This includes improved methods for the assessment of the health implications of decisions in other sectors (such as in the energy and transport sectors and in the water, food and agriculture sectors), and the improved integration of climate change mitigation, adaptation and health through "settings-based" research;
- improve decision-support, for example, research to improve vulnerability and adaptation assessments, operational predictions, and the understanding of decision-making processes;
- improve the public's understanding of these issues, and into what interventions and mitigation strategies will be deemed acceptable to which constituencies;
- estimate the costs of protecting health from the effects of climate change, including the characterisation of harmonized methods to estimate costs and benefits, the assessment of the health costs of inaction and the costs of adaptation, and improved economic assessment of the health co-benefits of climate and other environmental change mitigation [25,130–133].

Recommendations for research highlighted by the WHO are relevant to public health services development: (1) evidence of interactions of climate and other environmental change with other health determinants and trends; (2) knowledge of the direct and indirect effects of climate and other environmental change; (3) evidence on the effectiveness of short-term interventions; (4) evidence of health impacts of policies in non-health sectors; and (5) general public health skills deployed to strengthening public health systems to address the health effects of climate and other environmental change [132]. The inclusion of environmental public health in mainstream public health services, with

attendant capacity building of the service workforce, is likely required for development of a valid research evidence base in this area at the rapid rate at which it is needed [133].

In addition, in order to understand and follow the consequences of the complex interactions between human health and well-being and climate and other environmental change, it is important to have appropriate monitoring and data collecting systems in place. Environmental public health tracking at all levels (locally, nationally, regionally and globally) joined up through linkage of databases and standardized collection systems is an essential ingredient to pushing forward the science in this area [134]. A greater appreciation is required of the importance of big data involved in environment and human health collected by these environmental public health tracking systems [135]. The affected communities across the world require access to these data, while respecting issues of confidentiality, privacy and data governance [136]. Additionally, an important implication of both big data and the surveillance/monitoring systems is the need for new ways of thinking about and analyzing these data, learning from the experience of other scientific disciplines (such as oceanography or climate change modelling) in terms of improving modelling expertise over much broader time and spatial scales [135–137].

To gain an appropriate understanding of the impacts of wider environmental change on health, there is a need for a systematic attempt to assess the risks and benefits using a common framework. Addressing environmental change requires an inter-sectoral response—bridging health, environmental and industrial sectors. The need for risks from climate change to be assessed is mandated under the UK Climate Change Act (2008). A wider assessment of risks and benefits of broader environmental change and other factors is needed so that resources are appropriately allocated to adapting to our changing planetary environment [25].

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