Australian Government
Australian Institute of Health and Welfare

Benefits of the environment to health

A literature review of health benefits derived from 3 ecosystem services: air filtration, local climate regulation, and recreation

AIHW

Benefits of the environment to health

A literature review of health benefits derived from 3 ecosystem services: air filtration, local climate regulation, and recreation

Australian Institute of Health and Welfare
Canberra
Cat. no. PHE 311

The AIHW is an independent statutory Australian Government agency producing authoritative and accessible information and statistics to inform and support better policy and service delivery decisions, leading to better health and wellbeing for all Australians.

A complete list of the Institute's publications is available from the Institute's website www.aihw.gov.au.

ISBN 978-1-922802-07-1 (Online)
ISBN 978-1-922802-08-8 (Print)
DOI: 10.25816/j6vt-pb49

Suggested citation

Australian Institute of Health and Welfare (2022) *Benefits of the environment to health: A literature review of health benefits derived from 3 ecosystem services: air filtration, local climate regulation, and recreation*, catalogue number PHE 311, AIHW, Australian Government.

Any enquiries about or comments on this publication should be directed to:
Australian Institute of Health and Welfare
GPO Box 570
Canberra ACT 2601
Tel: (02) 6244 1000
Email: info@aihw.gov.au

Published by the Australian Institute of Health and Welfare.

Please note that there is the potential for minor revisions of data in this report. Please check the online version at www.aihw.gov.au for any amendments.

Contents

Summary

The value of the environment – to the economy and to human wellbeing – can be estimated through ecosystems accounts. Accounts on ecosystem assets and the services they provide can be compiled using the System of Environmental Economic Accounting Ecosystem Accounting (SEEA EA) framework adopted by the United Nations Statistical Commission in March 2021 (SEEA 2022).

In Australia, the Department of Climate Change, Energy, the Environment and Water (DCCEEW, formerly the Department of Agriculture, Water and the Environment – DAWE) is developing environmental ecosystem accounts. To do this, it is seeking to gain a wide understanding of the extent of the economic and social benefits of ecosystem services. It was in this context that the former DAWE commissioned the Australian Institute of Health and Welfare (AIHW) to conduct an extensive review of the evidence on ecosystem services and their benefits to, and impacts on, human health.

This review analyses a broad range of current relevant literature on the benefits of the following 3 ecosystem services for human health:

- air filtration – the filtering of air-borne pollutants by ecosystems, in particular by plants, to mitigate harmful effects of pollution
- local climate regulation – the regulation of ambient temperatures by plants and water bodies to improve local living conditions
- recreation-related services – the qualities of ecosystems that allow people to use and enjoy the environment, such as through providing opportunities for physical activity or other passive recreational pursuits.

An extensive review of available Australian and international literature found associations between ecosystem services and a range of health outcomes, although the evidence more strongly supported this relationship for some health outcomes than others. The review also sought to uncover existing research of health benefits of these ecosystem services in economic terms, in particular those using methods consistent with the SEEA EA framework.

The AIHW review revealed multiple examples of evidence in support of a wide range of health benefits associated with each of the 3 ecosystem services. Key health benefits included:

- air filtration is associated with improved respiratory outcomes (such as for asthma) and decreases in mortality. Positive maternal and perinatal outcomes are areas being increasingly researched.
- local climate regulation is associated with decreases in both all-cause mortality, and in hospitalisations due to heat.
- recreation-related services are associated with increases in both physical activity, and in subjective mental wellbeing associated with recreation in nature.

A range of other health benefits associated with these ecosystem services were also revealed, such as for cardiovascular health, heat-related mortality, obesity, diabetes, and immune function. However, the evidence for these tended to be inconsistent: some studies supported a positive association between the ecosystem service and the health benefit, while others found no association, or insufficient evidence to support one. In many cases, the equivocal findings could be attributed to design limitations in the original research articles. Inconclusive evidence does not necessarily mean an association does not exist – rather that the research approach may not have been the most appropriate for the research question.

1 Introduction

1.1 Purpose of the review

The Department of Climate Change, Energy, the Environment and Water (DCCEEW, formerly the Department of Agriculture, Water and the Environment – DAWE) is producing ecosystem accounts in Australia using the System of Environmental Economic Accounts Ecosystem Accounts (SEEA EA) framework. As ecosystem accounts should include information from a broad range of sectors, this framework calls for a collaborative approach to collecting and validating data (United Nations et al. 2021). Given the recognised important links between the environment and health, including knowledge from the health sector is key.

Accordingly, the purpose of this review is to survey and evaluate available literature on the impact of selected ecosystem services on human health to understand how they can contribute to health and how much of a health benefit they provide. The longer term purpose is to identify key data sources for determining links between ecosystem services and various health benefits (as measured by avoided negative health impacts, such as death and illness), which have the potential to support data development to monitor these impacts in line with SEEA EA accounting principles.

1.2 What is ecosystem services accounting?

Ecosystem services accounting is a system by which data about habitats, landscapes and other natural assets can be organised and linked to economic and other human activity (United Nations et al. 2021). The ecosystem accounts approach helps to describe changes in ecosystems and how these changes affect human wellbeing and economies (DAWE 2019).

The System of Environmental Economic Accounting (SEEA) is the accepted international standard for the provision of economic services accounting. It is produced and released by the United Nations, the European Commission, the Food and Agriculture Organization of the United Nations, the Organisation for Economic Co-operation and Development (OECD), the International Monetary Fund and the World Bank Group (United Nations et al. 2021).

The SEEA has 2 parts:

- The SEEA Central Framework (SEEA CF) was adopted in 2012 by the UN Statistical Commission as the first international standard for environmental–economic accounting. The framework looks at 'environmental assets' – such as water resources, energy resources, forests, fisheries – their use in the economy, and their returns to the environment as waste, air and water emissions.
- The SEEA Ecosystem Accounting (SEEA EA) complements the Central Framework and represents international efforts toward coherent ecosystem accounting. It takes the perspective of ecosystems and considers how individual environmental assets interact as part of natural processes within a given spatial area. Ecosystem accounts enable the presentation of indicators of the level and value of 'ecosystem services' in a given spatial area.

The SEEA approach can be used to help answer questions about the interactions between ecosystems and humans, such as:

- Who benefits and who is negatively affected by natural resource use?
- What is the impact of the state of the environment on specific sectors of the economy?

- How does the depletion of natural resources affect the income of a nation?
- Which ecosystem services are being generated, and who is benefiting from them?

In the Australian context, the DCCEEW uses 4 ‘building blocks’ of ecosystem accounts to illustrate the benefits that people receive from the environment (Figure 1.1).

Figure 1.1: Building blocks of ecosystems accounts

Source: DAWE 2019.

1.3 What are ecosystem services?

Ecosystem services are ‘the contributions of ecosystems to the benefits that are used in economic and other human activity’ (UN et al. 2021:27). In simple terms, they are the benefits that society gets from ecosystems, such as food, fuel, clean air and water, and recreational opportunities.

Ecosystem services can be derived from direct contact with nature, or via the transformation of resources and environmental assets (such as land, water and vegetation) into a flow of essential goods and services (such as food, shelter and clean drinking water) (Costanza et al. 1997).

The 3 domains of ecosystem services

The SEEA EA groups ecosystem services into 3 main domains, which incorporate the wide range of ecosystem services considered to be of substantial importance across many countries and in many settings. The main ecosystem service domains are:

- provisioning ecosystem services: those providing a benefit through harvesting or extracting products from nature
- regulating and maintenance ecosystem services: those arising from the ability of ecosystems to regulate biological processes and maintain environmental conditions via these processes
- cultural ecosystem services: those described by the SEEA EA as being ‘experiential and intangible services’, which are derived from the existence or function of ecosystems, and which provide a cultural benefit (United Nations et al. 2021).

See Appendix A, Table A1 for a complete list of ecosystem services, as included in the SEEA EA framework.

Ecosystem services affect human health in several ways. Some – in particular, those in the provisioning services domain – provide benefits that are the basis of human life (such as food, shelter and fuel). Others are important for maintaining healthy life, by preventing disease – for example, through regulating and maintaining ecosystem services of air filtration to remove pollutants, or through disease control to reduce disease-causing species. Cultural services largely offer wellbeing benefits – for example, their perceived benefits for mental wellbeing through connecting with or viewing nature; there are also less subjective benefits – for example, the health benefits of undertaking physical activity in urban parks or forests (United Nations et al. 2021).

1.4 Selection of ecosystem services for review

This review investigates the evidence of health impacts, and knowledge gaps, in relation to 3 ecosystem services. These services were selected (based on a background scan of the literature) as having particular relevance to health (including in the Australian context) via identifiable and potentially quantifiable mechanisms.

These 3 ecosystem services are:

- air filtration – a regulating and maintenance ecosystem service, involved in the removal of harmful particulate matter from the atmosphere, with the potential to affect respiratory, cardiovascular and other health outcomes
- local climate regulation – a regulating and maintenance ecosystem service, involved in regulating ambient local temperatures, and which plays an important role in protecting health, particularly during extreme temperature events
- recreation-related services – a cultural ecosystem service chosen for its potential to affect the risk factor of insufficient physical activity by providing opportunities for exercise-related endeavours, along with an exploration of other benefits, such as impact on mental health.

Ecosystem services provided by air filtration and local climate regulation were selected as, given the high proportion of urban dwellers in Australia, they have the potential to affect a large part of the country's population. Recreation-related ecosystem services were primarily chosen for their potential to provide opportunities to increase physical activity, given that 55% of Australian adults do not meet the guidelines for sufficient physical activity (AIHW 2020b). In 2018, 2.5% of the total burden of disease in Australia was attributable to insufficient physical activity (AIHW 2021b).

The selection of these ecosystem services is not meant to suggest that health benefits are limited to air filtration, local climate regulation and recreation-related services. All ecosystem services listed in the SEEA EA framework (see Appendix A, Table A1) ultimately have an impact on human health in some way.

- For example, provisioning services include crop, livestock, aquaculture and wood services, all of which support human life in providing basics such as food, fibre and fuel (United Nations et al. 2021). Absence of these basics would ultimately lead to death – for example, through hunger or exposure to the elements, although it may not be immediate; death may occur via a broad array of health pathways (such as vitamin deficiencies, adverse perinatal conditions, or heat or cold exposure). As such, while ultimately responsible for supporting human life, provisioning services could be considered more distal to immediate health impacts (that is, further removed from, as opposed to those that are proximal, or closer to, the health impacts).

However, a detailed examination of the literature in relation to all the proximal and distal impacts on health for all the services is beyond the scope of this review.

Also beyond the scope of this review is an evaluation of the health benefits of ecosystem services for indigenous people, as detailed in Box 1.1.

Box 1.1: Ecosystem services and Indigenous peoples

Internationally, ecosystem service frameworks are largely a product and function of Western concepts and research and are often unable to capture local indigenous concepts, such as the benefits of 'living on country' and human capabilities (for example , learning from Elders rather than via Western learning practices) (Sangha and Russell-Smith 2017). As such, researchers suggest that the ecosystem services of indigenous peoples should be considered on a case-by-case basis at the local level and, to be relevant, include consultation with the people living on country (Sangha et al. 2018; Sangha et al. 2019).

As well, much of ecosystem services accounting work relies on a Western definition of 'health' to quantify costs and benefits of ecosystem services, which does not adequately account for health in a way that is relevant to indigenous peoples. For example, Western understandings of health to do not account for the healing of intergenerational trauma due to colonisation, a key health concern of indigenous peoples.

Indigenous-specific frameworks are necessary to evaluate the value of ecosystem services to indigenous peoples. Indigenous peoples experience unique vulnerabilities to climate change and other rapid environmental changes, given their lives are 'so closely tied to the natural environment ' (Kosanic and Petzold 2020:2) and these frameworks must account for this position. Indigenous-specific frameworks generally have a different scope and are not readily compatible or comparable with frameworks based on Western ecosystem services and definitions of health, which, according to some Australian researchers, 'typically ignore' indigenous country-related capabilities and cultural norms essential for peoples' wellbeing and managing (looking after) country (Sangha and Russell-Smith 2017:265).

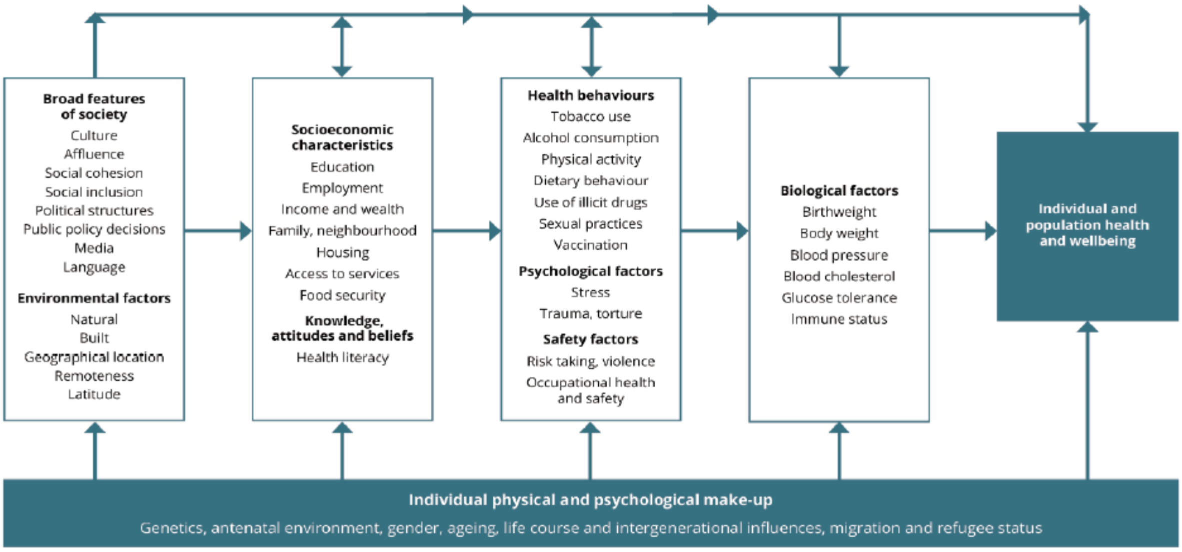
Furthermore, some research suggests that Payment for Ecosystem Services policies do not adequately account for indigenous cultures, values and practices. For example, research with the Ngemba Aboriginal people in the Murray–Darling Basin in Australia has found that the 'extended sense of deep interrelationships and flows between people, places, times and physical and metaphysical entities provides a more extensive challenge to conventional valuation methods' (Bark et al. 2019:247); furthermore, attempting to apply Western-based economic valuation methods to indigenous communities has the potential to harm and further disadvantage them, particularly if these methods are individually focused rather than community focused (Smith et al. 2019; Stoeckl et al. 2021).

For these reasons, it is not possible to adequately cover the ecosystem services of indigenous peoples within the time frames for this review, as this issue requires careful and concerted efforts to appropriately represent their relationships with ecosystem services (Kosanic and Petzold 2020).

1.5 Human health, health determinants and the environment

Human health is broadly considered as 'a state of complete physical, mental and social wellbeing and not merely the absence of disease or infirmity' (WHO 1946:2). Health reflects a complex interplay of genetics, lifestyle and environment. Factors influencing health that are separate from the physical and psychological make up of individuals are called the determinants of health (AIHW 2020c). Many factors within these determinants interact with each other, and ultimately work to affect human health (Figure 1.2). Often the determinants of health cannot be modified by the individual, and therefore informed and equitable public health policy is essential for promoting and protecting the health of individuals.

Figure 1.2: Framework for determinants of health



Source: AIHW 2020c.

Humans depend on the environment and its ecosystems to support life and provide good health – such as clean air, food, clean water, and fuel for energy; these are considered environmental determinants of health (Prüss-Üstün et al. 2017). While these determinants are distal to individual health, ecosystems are coming under increasing pressure as the planet's population increases – for example, from human activity, through over-consumption and alteration, leading to resource depletion (Whitmee et al. 2015). This is affecting the ability of the environment to continue to support healthy human life.

Rapid urbanisation is responsible for much of the pressure put on environmental systems. Globally, it is estimated that, by 2050, almost 70% of the world will reside in urban areas (United Nations Department of Economic and Social Affairs 2019). Australia is already highly urbanised, with around two-thirds of its population living in a major city; it is expected that this trend will continue in the future (ABS 2022). Increasing urbanisation carries many benefits, including employment, wealth and access to health services. However, it also places pressure on natural resources and on the ecosystem services they provide, and is associated with poor health outcomes, such as obesity, diabetes, coronary heart disease and psychiatric disorders (Engemann et al. 2020a; Kumar et al. 2006; Sobngwi et al. 2004). In response to evidence of the increasing harmful health effects of urbanisation, global research interest in the relationship between the natural environment and human health is steadily growing (Frumkin et al. 2017; Hartig et al. 2014).

Climate change, which is putting further pressure on the earth and human health, has been labelled as the biggest threat to health in the 21st century (WHO 6 October 2015). Climate change – together with climate variability that leads to higher temperatures, heavy rainfall, and increased flooding and bushfires – is associated with increases in vector-borne diseases (such as dengue and chikungunya virus), diarrhoeal and other gastrointestinal disease, certain respiratory conditions, cardiovascular disease risk and mental illness (for example, due to trauma after experiencing a traumatic climate change event, such as extreme bushfire) (Cissé et al. forthcoming 2022). It is predicted that, by 2050, as a result of climate change, there will be more than 250,000 deaths per year due to climate change-related heat, poor nutrition, malaria and diarrhoeal disease alone (Cissé et al. forthcoming 2022).

Recognising the interplay between humans and the environment is of major importance to protecting human health into the future. To guide and monitor this, several key policies and strategies have been developed globally and in Australia, including the United Nations Sustainable Development Goals, the World Health Organization Global Strategy on Health, Environment and Climate Change, and Australia's National Preventive Health Strategy.

United Nations Sustainable Development Goals

In 2015, the United Nations adopted the Sustainable Development Goals, a set of 17 goals to focus global attention on achieving a better and more sustainable future for all, as a new approach for the environment, health and equity (United Nations General Assembly 2015). These goals identify the key challenges facing the world, with a spotlight on the need for action on the environment and climate change, and recognise the interlinkages between human conditions (poverty, hunger, education, health) and the environment. In particular, 9 of the 17 goals specifically incorporate both the environment and health:

- Goal 1 – end poverty in all its forms everywhere
- Goal 2 – end hunger, achieve food security and improved nutrition, and promote sustainable agriculture
- Goal 3 – ensure healthy lives and promote wellbeing for all at all ages
- Goal 6 – ensure availability and sustainable management of water and sanitation for all
- Goal 7 – ensure access to affordable, reliable, sustainable and modern energy for all
- Goal 8 – promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all
- Goal 11 – make cities and human settlements inclusive, safe, resilient and sustainable
- Goal 12 – ensure sustainable consumption and production patterns
- Goal 13 – take urgent actions to combat climate change and its impacts (WHO 2020).

World Health Organization Global Strategy on Health, Environment and Climate Change

To counter the impacts of environmental change (including climate change and loss of biodiversity) on human health, the World Health Organization produced the Global Strategy on Health, Environment and Climate Change (WHO 2020). The strategy's key vision was:

> '… a world in which sustainable development has eliminated the almost one quarter of the disease burden caused by unhealthy environments, through health protection and promotion, good public health standards, preventive action in relevant sectors and health life choices, and which manages environmental risks to health' (WHO 2020:7).

The strategy aims to guide the health community in responding to health risks from the environment (in particular those parts of the environment that can 'reasonably be modified') (WHO 2020:3), with the environmental health risks being defined as the 'physical, chemical, biological and work-related factors external to a person, and all related behaviours' (WHO 2020:3). Furthermore, the strategy aims to achieve its objectives by scaling up primary prevention, engaging cross-sectoral action through a 'Health in All Policies' approach, and by monitoring progress towards the Sustainable Development Goals.

The World Health Organization strategy highlights that both human health and the environment need to be considered when planning for the projected increase in global urbanisation. Otherwise, harmful health effects will likely result from increased air pollution, noise and heat exposure, and from decreasing physical activity due to unsustainable transport systems and reduced access to urban green space (WHO 2020).

National and local approaches

Australia fares well in terms of health, as measured by a range of factors such as life expectancy at birth, deaths due to diseases of the circulatory system, and infant mortality (AIHW 2022b). For example, according to statistics from the OECD, Australia ranks above the OECD average on each of these measures (AIHW 2022b). However, recent climate-driven events – such as the 2019–2020 bushfire season and rises in the number of extreme heat events – are a reminder that the environment in Australia can have a direct impact on health (Beggs et al. 2019).

Although there is currently no overarching national environmental health policy in Australia, the impact of the environment is being increasingly considered. For example:

- monitoring of the Sustainable Development Goals: Although there is no agenda for achieving these goals, Australia does monitor progress towards this end, including for those goals relating to health and the environment (see www.sdgdata.gov.au for details on monitoring and progress)
- National Preventive Health Strategy 2021–2030 (Department of Health 2021): The strategy – whose vision is to 'build a sustainable prevention system for the future' – emphasises the need for mitigation strategies against future environmental and climatic threats to human health. It also calls for a 'Health in All Policies' approach (WHO 2014) to make human health a priority across all sectors.

Much work is also being done by states, territories and non-government organisations, for example, on monitoring the impact of various environmental factors and health.

The focus on health and the environment, both internationally and within Australia, indicates an increasing recognition that human health and the environment are inextricably linked and that both are currently under threat, largely due to human pressures on the environment. Protecting ecosystems and maximising ecosystem services for human health involves a 'whole of society' approach, with multiple sectors and the community involved.

1.6 Methodology

The purpose of the AIHW review was to extensively search the literature around the 3 selected ecosystem services to investigate the links between them and health – looking, in particular, for studies conducted in line with the SEEA EA framework. The approach commenced with a search of the academic literature. In addition, a search of the grey literature (non-academic publications by various institutions, government and non-government agencies and organisations) was conducted for case studies involving ecosystem services and their impact on health. The following paragraphs detail the search methodology used for this review.

Relevant academic literature was identified by searches of online health and medical databases with combinations of terms relating to ecosystem services, air pollution, local climate, temperature, recreation, and human health. The search was supplemented with citation searches (also known as snowballing) from the selected texts. This ensured that further important literature was included, and access was not limited to specific databases. Additional articles were also included, based on consultations with subject matter experts.

The inclusion criteria for the academic literature search were 'English language', 'research and review articles', 'published between 2011 and 2021'. No restrictions were placed on the type of study included (for example, cohort or cross-sectional) other than reviews of reviews, which were excluded. The time frame was limited to the last 10 years to ensure that the evidence reviewed was up to date with the latest scientific literature. The exception to this time frame was relevant articles identified in citation searches or through expert review that were deemed to be of particular importance to the subject matter. Exclusion criteria for the academic literature search, besides reviews of reviews, were non-English language, non-research articles (for example, book chapters, grey literature). See Appendix B for a summary of the eligible articles for each ecosystem service that were included in this review.

The subsequent supplementary search of the grey literature was included to investigate real-life applications of ecosystem-based strategies implemented to improve public health, with a particular focus on case studies from Australia or comparable countries. Some examples of these strategies and their measured health impacts are included in each section, including urban cooling initiatives, urban greening and walkable cities. The only exclusion criterion for this search was non-English language documents. Information on each of these case studies is in the main body of the review.

The method used for this review was not systematic review methodology, and the search strategy was not designed to include a quality assessment of the literature. Rather, it was designed as an initial overview of the topic to bring together relevant information.

2 Ecosystem services and health – background and terminology

To explore, measure and explain the health impacts of air filtration, local climate and recreation-related ecosystem services requires an understanding of the terminologies and methodologies used in both health research and ecosystem services research. This section provides the background context for the AIHW review. It explains the key concepts common to the 3 ecosystem services and the measurement of the health impacts, in terms of describing and measuring the ecosystems, defining health and wellbeing, and outlining some common methodologies for measuring health and attributing impacts of environments to health outcomes.

2.1 What is nature?

In its purest form, nature could be considered as the 'physical features and processes of nonhuman origin', including flora and fauna and other geographic formations (Hartig et al. 2014:208). However, based on the hypothesis of biophilia, which posits that humans have a genetically programmed affiliation for living things (Kellert and Wilson 1993), humans have introduced elements of nature into their everyday surroundings. Therefore, the definition of nature has expanded to include elements that are built and maintained by humans to provide them with access to, and interaction with, nature in their daily lives (Hartig et al. 2014), such as community gardens, parks or residential gardens. Hence, the literature on this topic commonly uses the term 'nature' interchangeably with terms that describe any form of vegetation, such as 'greenness', 'greenspace' / 'green space', and other permutations of this nomenclature (for example, 'blue space' for water elements).

Green space

Green space is perhaps the most important environmental exposure in this review and has several definitions in the literature. The term is classically defined as 'land covered with some form of vegetation' (Warren 1973:2), where vegetation generally refers to trees; it is also commonly considered synonymous with other terms such as green infrastructure, urban vegetation, or urban parks and woodlands (Doick et al. 2013). Taylor and Hochuli (2017) highlight that many studies do not provide an explicit definition of the term. Overall, the authors concluded that, while multiple meanings of the term exist, green space broadly encompasses 'areas with natural vegetation, such as grass, plants, or trees', as described by Lachowycz and Jones (2013:62).

It is important to note that, while the term can be used to refer to urban vegetation such as urban parks, street trees and vegetated sky rises, this does not preclude its use in describing vegetation outside urban settings. Furthermore, due to difficulties in measuring green space, its use throughout the literature may be implicitly limited to vegetation that is publicly accessible, which might understate the ecosystem service benefits afforded by private green space (such as gardens restricted from public accessibility). In this review, the term 'green space' is used to refer to vegetation or land covered by features of vegetation, irrespective of whether publicly accessible or not.

Green space is quantified using several measures, most commonly the normalized difference vegetation index (NDVI) (see Box 2.1). Another common measure is tree canopy coverage – that is, the proportion of an area covered by trees when viewed from the sky –

which tends to be estimated based on land cover maps (Nowak et al. 1996). Tree canopy coverage has been argued to offer a better measure of green space than the NDVI as it provides direct data on vegetation type and quantity and can therefore be used to track fluctuations in vegetation over time. As the NDVI is based on surface reflectance (see Box 2.1), it can provide only an estimate, based on inference, of the type of vegetation in an area.

Box 2.1: What is the normalized difference vegetation index?

NDVI is based on the light-reflecting properties of vegetation. It is derived from satellite measurement data, and used to indicate the degree to which an area or region contains vegetation. Non-vegetated areas, and areas of vegetation in poor health (and therefore less green) tend to reflect visible light, while healthy vegetation absorbs it. By taking satellite imaging data and applying a basic formula to correct for these differences in light reflectance, land surface that contains vegetation presents as 'greener' than land surface that does not contain vegetation.

The NDVI is widely used in ecosystem services literature. Both the quantity and variability in the NDVI have been associated with various health outcomes (Pereira et al. 2012), and it is relevant to the 3 ecosystem services presented in this report. However, NDVI does not measure green 'space' *per se* – rather vegetation health. Therefore, it cannot differentiate between the type or quality of green space (such as trees, shrubs and grass), nor can it discern differences in the patterns of access and/or exposure to green space in a population (Holland et al. 2021).

These limitations are noteworthy in that some evidence suggests the ecosystem service benefits of green space on human health vary based on its type and distribution (Shen and Lung 2016). Some data also show that different types of green space, such as tree canopy and open grass, may have differing associations with human health outcomes (Astell-Burt and Feng 2022). Because of these and other concerns, the widespread use of NDVI has been criticised for potentially underestimating vegetation provision within higher density cities (Astell Burt and Feng 2022). Nevertheless, many studies do use NDVI as their chosen measure of green space.

NDVI values range from –1 to +1, where –1 indicates water, 0 reflects no vegetation and +1 represents a high density of vegetation (Son et al. 2016; Weier and Herring 2000). NDVI ranges are commonly reported in units, such as tertiles or quartiles, which describe the range of NDVI values in terms of thirds or quarters (respectively) of the overall distribution of values.

Blue space

With half of the world's population living within 3 km of fresh water (Kummu et al. 2011), most urban settings in the world have a form of 'blue space' such as lakes, rivers and fountains. Blue space complements urban sustainability by providing sustainable drainage and rainwater harvesting, and areas for recreation and physical activity (Gunawardena et al. 2017).

Research has traditionally considered blue space alongside green space (Bell et al. 2019; Smith et al. 2021). More recently, researchers have turned their focus to blue space directly. To date, a consensus definition of the term does not exist. Some definitions in research include 'all surface waters within a city' (Volker et al. 2013:355), 'areas dominated by surface waterbodies or watercourses' (Gunawardena et al. 2017:1041), 'outdoor environments – either natural or manmade – that prominently feature water and are accessible to humans' (Grellier et al. 2017:3), and 'all forms of natural and manmade surface water' (Smith et al.

2021:1). In general, the term ‘blue space’ will be used here to refer to any area or surface made up of water.

Blue space is often measured using either the presence of bodies of water or, more specifically, the percentage of blue space coverage within a defined area, or proximity to blue space from a defined area. Both these measures are commonly derived through land cover maps or geographic information system tools.

2.2 Health and wellbeing

An array of factors can influence health outcomes, including genetics, lifestyle / behavioural factors and the environment (AIHW 2020c). Those elements with potential to produce negative health outcomes are referred to as risk factors.

The term ‘wellbeing’ is broad and encompasses a combination of interrelated concepts that include physical, mental, emotional and social health that, together, to make up an individual’s quality of life. The World Health Organization explicitly links health with wellbeing (WHO 1946), recognising that a person’s physiological health status is closely associated with less tangible qualities like social relationships and connectedness. The OECD describes wellbeing as multidimensional, involving a range of aspects of life such as civic engagement, social connections, housing, income, knowledge and skills, and health status (OECD 2021). Certain elements of wellbeing can be particularly difficult to measure and interpret (for example, happiness, confidence, fair treatment); however, many other factors that shape wellbeing can be measured. Some frequently measured outcomes include a person’s housing status, labour force participation, education, perception of safety in the community, disposable income and community engagement (AIHW 2021d).

Understanding the health of a population is important for policy and planning purposes. A useful method to quantify health in a consistent and comparable way is to assess the burden of disease in the population (see Box 2.2).

Box 2.2: Burden of disease, population attributable burden and population attributable fraction

Burden of disease measures the impact of living with illness and injury and dying prematurely. The summary measure ‘disability-adjusted life years’ (or DALY) is used to measure the years of healthy life lost due to death and illness from a particular disease.

The disease burden attributed to a selected risk factor for death or illness, such as air pollution, is known as ‘attributable burden’. Attributable burden reflects the reduction in fatal burden (measured by years of life lost, or YLL) and non-fatal burden (measured by years lived with disability, or YLD) that would have occurred if exposure to the risk factor had been avoided or reduced to its lowest level (AIHW 2020a).

The population attributable fraction (PAF) is the proportion of a particular disease that could have been avoided if the population had never been exposed to a risk factor. Calculating PAFs requires, as inputs, the relative risk (the increased risk of developing or dying from the disease if exposed to the risk factor) and the prevalence of exposure to the risk factor in the population (AIHW 2021a).

2.3 What evidence connects nature to health and wellbeing?

It has long been known that exposure to 'nature' has positive impacts on health and wellbeing (Hartig et al. 2014); this is supported by a vast body of literature covering a wide array of nature types and health outcomes.

Research has measured health outcomes at the individual level and the biomedical level (for example, through testing of salivary cortisol levels) through to much larger scale population-level studies (using administrative data sets) (Hartig et al. 2014; Pröbstl-Haider 2015); while all contribute to the knowledge base for the link between health and nature, this heterogeneity needs to be considered in interpreting results.

Likewise, definitions and measures of 'nature', 'greenness' and 'green space' vary widely, making comparisons between studies difficult. Many studies look only at the association between the existence of nature and a particular health outcome, while others use statistical methods, such as mediation analyses (see Box 2.3), to try to determine causal pathways between nature and health. However, in many cases, the causal mechanism for the association remains unclear, with the research either not investigating, or failing to determine, the underlying causal mechanism for the health benefit associated with green space.

Nonetheless, results from the many reviews, empirical studies and meta-analyses conducted on nature and health have shown that an association between green space exposure and health and wellbeing exists, and that more contact with nature is generally linked to better health outcomes, even after adjusting for other factors, such as demographics, health behaviours (for example, smoking), and socioeconomic status (Kuo 2015).

Box 2.3: Causal mechanisms and mediation analysis

A causal pathway is the connection between an exposure and an outcome. A good example of a causal pathway is the path between smoking as an exposure and lung cancer as an outcome. While there is sufficient evidence to support smoking as a key risk factor for lung cancer, there may be other factors involved in the outcome of lung cancer. For example, a family history of lung cancer, or exposure to certain chemicals in the workplace, may also lie along this pathway and interfere with the direct link between smoking as the exposure and lung cancer as the outcome. Factors that are the mechanisms in the relationship between the exposure and outcome variables are called mediating variables.

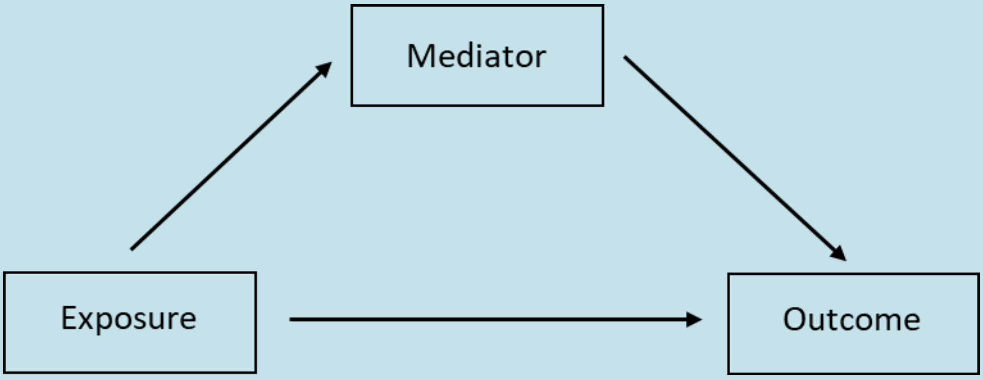
Conversely, a factor that affects the relationship between the exposure and outcome variables in a way that makes them seem related when they are not is called a confounding variable. Good study design aims to identify confounding variables and adjust for them in the analysis in a way that removes this distortion of the relationship.

Mediation analysis is a statistical technique that serves to clarify the nature of the relationship between an exposure and an outcome. It requires 3 variables – an exposure, an outcome and a hypothesised mediator (that is, something thought to be influenced by the exposure, which in turn influences the outcome). One way to think about mediation is that

(continued)

Box 2.3 (continued): Causal mechanisms and mediation analysis

the mediator is intermediate or *in between* the exposure and the outcome – it is what is thought to explain the relationship, or transmit the effect, from the exposure to the outcome.



From an ecosystem services perspective, consider, as an example, the relationship between green space and human health. Why might green space be associated with fewer negative health outcomes? A possible reason is that green space (such as urban vegetation) improves air quality, which in turn leads to fewer detrimental health effects associated with air pollution (such as asthma). In this example, the relationship between green space and health is mediated by air quality – green space is the exposure, health is the outcome, and air quality is the mediator. Any effect that green space has on health through air quality is referred to as the *indirect* effect, whereas any effect that green space has on health independent of air quality is referred to as the *direct* effect.

As with all statistical methods, mediation analysis has its uses and limitations. Newer methods, such as causal mediation analysis, have been developed to overcome some of these limitations. However, few of the studies included in this review employed these newer methods. This corresponds with recent evidence on the use of different mediation models in observational research, which found low uptake of causal mediation analysis (Rijnhart et al. 2021).

Sources: Anselmi et al. 2017; Yang et al. 2021.

Extensive evidence on the health-supportive benefits of nature has been reported elsewhere (Bowler et al. 2010a; Haluza et al. 2014; Hartig et al. 2014). Some specific examples of health benefits of nature are outlined in the following subsections, along with the health impacts of diseases and risk factors. Many of the resulting conditions that would occur in the absence of these health benefits are major contributors to the burden of disease, globally and in Australia, and are large contributors to health system spending.

All-cause mortality

Several meta-analyses have shown that living in areas with green space lowers deaths from any cause. Twohig-Bennett and Jones (2018) found that those living in areas of highest green space had significantly lower odds of dying from any cause (that is, all-cause mortality) than those living in lowest green space areas (odds ratio, OR, of 0.69). Gascon et al. (2016) reported an 8% lower risk of all-cause mortality in areas of high green space compared with low green space. Rojas-Rueda et al. (2019) conducted a meta-analysis of longitudinal cohort studies, finding a lower risk of all-cause mortality with increasing residential green space –

specifically, a pooled hazard ratio (HR) for all-cause mortality of 0.96 with a 0.1 unit increase in NDVI (a measure of green space, see Box 2.4).

Cardiovascular health

Korean adults living in urban areas of highest green space had a 15% lower relative hazard of total cardiovascular disease (HR 0.85), a 17% lower relative hazard of coronary heart disease (HR 0.83), a 23% lower relative hazard of acute myocardial infarction (HR 0.77), a 13% lower relative hazard of total stroke (HR 0.87) and a 14% lower relative hazard of ischaemic stroke (HR 0.86) compared with those adults living in urban areas of lowest green space (Seo et al. 2019).

Adults in the United Kingdom living in the greenest neighbourhoods had a 7% lower relative hazard rate of developing cardiovascular disease than adults living in the areas of least greenness (Dalton and Jones 2019).

A longitudinal study of adults aged 45 and over living in the Australian cities of Sydney, Wollongong and Newcastle found that those living in areas with 30% or more tree canopy within a 1.6 km buffer zone of their residence had lower odds of incident cardiovascular disease (OR 0.78) and incident hypertension (OR 0.83) than those living in areas with 0–9% tree canopy (Astell-Burt and Feng 2020).

Cardiovascular diseases (such as coronary heart disease and stroke) are the major contributors to disease burden in Australia. In 2018, they were one of the leading disease groups contributing to the total (fatal plus non-fatal) burden of disease, accounting for 13% of the total burden (AIHW 2021a). In 2018–19, expenditure on cardiovascular disease was $11,821 million, which accounted for 8.8% of total disease spending (AIHW 2021c).

Box 2.4: Measuring the difference – measures of effect size

Effect size is a statistical way to measure the strength of a relationship between 2 variables, or the magnitude of the difference between 2 groups in a study. This can be expressed in different ways, and the choice of measure depends on the study type. Research included in this review discusses effect sizes in terms of:

- rate ratios, also referred to as relative risk (RRs)
- odds ratios (ORs)
- hazard ratios (HRs).

RRs and ORs concern exposures and outcomes, while HRs concern rates of change.

For RRs and ORs, a value of 1 means the effect is the same for both interventions. For RRs, a value <1 means an event is less likely to occur and a value >1 means it is more likely to occur. For ORs, a value of <1 means the exposure is associated with lower odds of an outcome, while values >1 mean that the exposure is associated with higher odds of an outcome.

For HRs, a value of 1 means that the likelihood of the event's occurring is equal in both groups at any given time. Values <1 or >1 indicate that the event is not occurring at an equal rate, and the risk of an individual in one group is not equal to the risk of an individual in the other group at any given time.

Type 2 diabetes

ORs of type 2 diabetes decreased with increasing neighbourhood green space, from 0.97 in the area of lowest green space to 0.67 in the area of highest green space (Bodicoat et al. 2014). A longitudinal study of adults aged 45 and over living in the Australian cities of Sydney, Wollongong and Newcastle found that those living in areas with 30% or more tree canopy within a 1.6 km buffer zone of their residence had lower odds of incident diabetes (OR 0.69) than those living in areas with 0–9% tree canopy (Astell-Burt and Feng 2020).

In 2018, type 2 diabetes accounted for 2.3% of the total disease burden in Australia, ranking 12th among the leading 20 causes of disease burden in 2018 (AIHW 2021b). In 2018–2019, total health system spending attributable to high blood plasma glucose (including type 2 diabetes) was $3,187 million (the third highest amount of attributable spending due to risk factors) (AIHW 2022a).

Overweight and obesity

A review by Lachowycz and Jones (2011) found a positive (though, in some cases, weak) association between green space and 'obesity-related indicators' – that is, physical activity (mostly self-reported, some using accelerometers), weight status (for example, self-reported or objectively measured body mass index, or BMI) and obesity-related health outcomes (such as coronary heart disease, diabetes and mortality from circulatory disease). However, evidence was mixed and varied by age, socioeconomic status and how green space was measured.

An Australian study based in Perth, Western Australia found an association between living in areas with greater amounts of greenness (as measured by NDVI) – and with greater variation in green space (that is, mixed-use spaces that include green space and built infrastructure) – and lower odds of overweight-and-obesity in adults. After adjusting for potential confounders, the odds of being overweight or obese was 0.84 for those living in areas with the highest amount of greenness, and 0.75 for those living in areas with the highest variation in greenness, compared with those living in areas with the lowest amount and variation of greenness (Pereira et al. 2013).

In 2018, 8.4% of the total burden of disease in Australia was due to overweight (including obesity). This was the leading risk factor contributing to non-fatal burden (living with disease), and the second leading risk factor for total burden, after tobacco use (8.6%) (AIHW 2021b). In 2018–2019, total health system spending attributable to overweight (including obesity) was $4,268 million, which is the highest health system expenditure attributable to risk factors (AIHW 2022a).

Mental health

A cohort study based in the Australian cities of Sydney, Wollongong and Newcastle found that residing within a 1.6 km buffer zone with 30% or more tree canopy was associated with 31% lower odds of incident psychological distress (OR 0.69) compared with those living in buffer zones with the lowest percentage of tree canopy (Astell-Burt and Feng 2019).

Other findings in relation to the impact of nature on mental health include higher levels of neighbourhood green space being significantly associated with lower levels of self-assessed depression, anxiety and stress (Beyer et al. 2014), and increased green space and higher density of street trees being found to be associated with decreased prescribing of antidepressants (Helbich et al. 2018; Marselle et al. 2020).

Mental and substance use disorders (excluding suicide) contributed to 13% of the total burden of disease in Australia in 2018, making it one of the highest ranked disease groups (AIHW 2021b). Mental and substance use disorders were the second highest disease group contributing to non-fatal burden (24%) (AIHW 2021a). In 2018–2019, expenditure on mental and substance use disorders was $9,609 million, which accounted for 7.2% of disease spending (AIHW 2021c).

Stress

People exposed to green space for 25.5 hours a week scored 3.1% lower (that is, they had less perceived stress) on the Perceived Stress Scale (a subjective measure of stress) than those who had no green space exposure (Hazer et al. 2018). A meta-analysis of studies looking at the health benefits of green space exposure (which included several studies using objective measures of stress) found significant associations between greater exposure to green space and lower salivary cortisol levels, lower heart rate and lower diastolic blood pressure (Twohig-Bennett and Jones 2018). While the broad variation in definitions and measurement methods for stress make it difficult to quantify at the population level, the evidence consistently supports a positive association between exposure to nature and stress reduction.

Insufficient physical activity (as a health risk factor)

Insufficient physical activity is a known risk factor for numerous health conditions (AIHW 2020b). Research has shown that residing near public open space can encourage physical activity – with a consequent potential to positively affect health.

A study by Giles-Corti and others (2013) found that, for every additional type of recreational destination within an urban residential area, recreational walking increased by 17.6 minutes per week. A survey-based longitudinal cohort study in Brisbane, Australia – which examined park use in relation to physical activity levels – found that those who used public parks regularly had higher odds of meeting recommended physical activity guidelines (OR 1.35) than those who did not regularly use a park, and that there was a positive association between the larger park size and greater amounts of time spent doing moderate- to vigorous-intensity physical activity (compared with non-park users) (Hooper et al. 2020). Health and wellbeing benefits shown to flow from undertaking exercising in nature include positive impacts on energy levels, mental wellbeing, anxiety and mood (Mackay and Neill 2010; Pretty et al. 2007; Thompson Coon et al. 2011). As physical activity benefits physical health, and exposure to nature benefits mental health and wellbeing, it is thought that the health benefits of exercising in nature are simultaneously derived from undertaking physical activity and from being in contact with the natural environment (Loureiro and Veloso 2017). Thus, exercising in nature potentially has greater benefits than performing the same activity in an artificial environment (Bowler et al. 2010a).

In 2018, insufficient physical activity was responsible for 2.5% of the total burden of disease due to an increased risk of a range of conditions, such as type 2 diabetes, coronary heart disease, certain cancers, dementia and stroke (AIHW 2021a). In 2018–2019, total health system spending attributable to physical inactivity was $561 million (AIHW 2022a).

Immune function

Inhalation of biogenic volatile organic compounds (BVOCs) produced by plants has been shown to increase immunity by stimulating natural killer cells with anti-cancer properties

(Kuo 2015), and exposure to micro-organisms in natural settings may stimulate immune function, according to the 'hygiene hypothesis' (Frumkin et al. 2017).

Despite these, and other, examples showing an association between nature or greenness, and health, some evidence is equivocal. For example, a study by Richardson and others (2012) found increased all-cause mortality in areas of greatest greenness, while another study found an association between increasing green space and decreasing deaths from cardiovascular and respiratory causes among men but not women (Richardson and Mitchell 2010).

As well, the research is in part hampered by study design limitations – for example, cross-sectional studies cannot identify causality, and they risk identifying reverse causality (for example, does living in greener areas result in better health, or are people with better health more likely to live in areas of greater greenness?). Other limitations include:

- measurement of greenness: measuring total amounts of vegetation within a radius of peoples' homes, for example, does not account for people's total exposure across time, nor can it account for actual use of available green space; as well, the methods for measuring greenness vary, with many relying on what is considered the sub-optimal method of NDVI
- measurement of health: the wide array of tools used to measure health behaviours and outcomes limits comparability between studies
- use of meta-analyses of pooled data: the data selected for inclusion may have limited comparability
- studies that measure biomedical aspects: these studies are often limited to small numbers of participants and therefore lack generalisability.

Importantly, many of the studies that show the benefits of nature on health rely on a reported association between exposure to nature and the health outcome, but do not specifically attribute the effect to an ecosystem service – for example, whether the better cardiac outcomes seen among those living in areas of greater green space are due to better air quality, better local climate, or better mental health and higher physical activity levels as a result of spending time in nature.

The following chapters discuss these concepts in detail in relation to the ecosystem services of air filtration, local climate regulation and recreation-related ecosystem services, and provide an in-depth assessment of the literature supporting direct links between these ecosystem services and human health.

3 Air filtration services

3.1 What is air pollution?

Air pollution is the presence of substances in the air that pose a risk to human health and quality of life (Brunekreef and Holgate 2002; WHO 2021). Air pollution comprises a mix of gaseous, liquid and solid particles, such as carbon monoxide (CO), nitrogen dioxide (NO_2), ozone (O_3), particulate matter (commonly measured as particles of less than 10 microns (PM10) or 2.5 microns (PM2.5) in diameter) and sulphur dioxide (SO_2) (AIHW 2010; Brook et al. 2004). Pollutants can be categorised as:

- primary pollutants: those that are emitted directly into the air
- secondary pollutants: those that undergo chemical changes or transformation, such as when nitrogen dioxide (NO_2) or volatile organic compounds (VOCs) are converted by the sun to produce ozone (O_3) or particulate matter (AIHW 2010; Pope and Dockery 2006).

Air pollution can be caused by natural phenomena, such as bushfires and dust storms, and by man-made (anthropogenic) processes, such as industry and vehicle use.

3.2 How does air pollution affect human health?

Research has consistently shown that air pollution has a negative impact on human health, affecting almost every organ in the body (Schraufnagel et al. 2019, WHO 2021). Gaseous pollutants (such as NO_2 and O_3) and particulate matter enter the body through inhalation into the lungs, where they can cause local inflammation, be transported to other parts of the body via the bloodstream, and damage internal tissues (either directly, due to their toxicity, or by causing inflammation and fibrosis) (Schraufnagel et al. 2019).

Children are particularly susceptible to the health effects of ambient air pollution because of the potentially irreversible damage the pollutants can do while the respiratory system, and other organs, are developing in the prenatal period and in early childhood (Schraufnagel et al. 2019) and because children inhale a greater volume per body mass of pollutants than adults when exposed to the same amounts of air pollution (Bateson and Schwartz 2008; Schraufnagel et al. 2019; WHO 2018).

Other susceptible groups include people with pre-existing conditions (such as asthma or chronic obstructive pulmonary disease, or COPD), the elderly, and pregnant women (Bentayeb et al. 2012; Ha et al. 2014; Hooper and Kaufman 2018; Pedersen et al. 2014).

3.3 Disease burden and expenditure due to air pollution in Australia

In Australia, ambient air pollution poses a much lower risk to human health than in developing countries, as is the case in other high-income countries (GBD 2019). However, this may increase in the future, with population growth, urbanisation and increased transport and energy demands being identified in the 2015 National Clean Air Agreement as key risks to future air quality in Australia (Department of the Environment 2015). Furthermore, predicted increases in bushfire events in Australia due to climate change will lead to periodic decreases in air quality (Borchers Arriagada et al. 2020).

Even at current low levels, air pollution affects the health of Australians. The most recent Australian Burden of Disease Study (AIHW 2021a) found that 1.3% of the total burden of disease in Australia in 2018 was due to air pollution, and that 0.9% was due to dying prematurely – equivalent to around 3,236 or 2% of all deaths. For comparison, this is about 2.8 times as high as the number of road fatalities for the same period, with 1,145 road deaths involving motor vehicle occupants, motor bikes, bicycles and pedestrians (BITRE 2019).

Coronary heart disease was the largest cause of attributable burden (42%), with the remainder attributable to COPD, stroke, type 2 diabetes, lung cancer and lower respiratory infections (AIHW 2021a).

In 2018–19, health system spending attributable to air pollution was $352 million. Air pollution contributed to around 4.0% ($94 million) and 6.1% ($57 million) of total health expenditure on coronary heart disease and COPD, respectively (AIHW 2022a).

3.4 What is air filtration?

Air filtration is a regulating ecosystem service, defined as 'the ecosystem contributions to the filtering of airborne pollutants through the deposition, uptake, fixing and storage of pollutants by ecosystem components, particularly plants, that mitigates [sic] the harmful effects of the pollutants' (UN et al. 2021:132).

Air filtration of particulate matter can occur in several ways. Airborne particulate matter can be deposited onto leaf or bark surfaces of trees, shrubs or grasses, where it is retained. This deposition is temporary, as the particles can be resuspended by air flow, or washed off by rain (Nowak et al. 2018). Additionally, vegetation – in particular trees, but also shrubs and other types of vegetation – are able to physically alter the pathways through which airborne particles travel by providing a type of barrier or buffer (Diener and Mudu 2021). Gaseous pollution, on the other hand, is removed by the diffusion of gases through the leaf stomata (minute openings in the epidermis of leaves, stems and other plant organs), where it is then absorbed into the leaf structure (Nowak et al. 2018).

The amount of particulate matter that vegetation can remove depends on several different factors, such as:

- the type of leaf surface – for example, rougher, waxier surfaces tend to hold more particulate matter (Janhäll 2015)
- the design and layout of the vegetation – for example, roadside vegetation should be located close to the emission source (that is, cars) to be able to come into contact with the pollutants, and should be low enough to allow for the air above to dilute the pollution. As well, the vegetation should be porous enough to allow air to pass through it, as air that does not pass through vegetation cannot be filtered (Janhäll 2015)
- the seasonal variations and the percentage of evergreen species – smaller amounts of air pollution are removed in leaf-off seasons (Nowak et al. 2018).

Areas with greater complexity in vegetation – such as those with trees, shrubs and herbaceous species that do not require regular maintenance in terms of watering and fertilising – provide better air filtration capabilities than more homogenous vegetation such as highly managed lawns and planted trees (Vieira et al. 2018).

Despite these local-level variations, trees, grasslands and shrublands have been shown to remove tonnes of air pollution annually (Gopalakrishnan et al. 2018; Nowak et al. 2006; Nowak et al. 2018) which, in the context of the human health benefits derived from decreasing ambient air pollution, underlies the importance of air filtration as an ecosystem service.

3.5 Overview of the literature

Much research links green space and health, and air pollution and health. There is less evidence, however, on the causal pathways by which green space affects air pollution so as to have positive or negative health.

The search strategy for this review identified 33 eligible articles exploring the link between air pollution, ecosystem services supplied by green space or vegetation (in terms of air filtration), and human health:

- 26 presented some form of original research (including modelling and analysis studies)
- 7 reviewed the literature on air filtration services and human health, one of which applied causal criteria analysis to the review findings

The articles selected for inclusion in the AIHW review covered a broad range of health conditions, locations, vegetation, and study types (including monetary valuation), and have been grouped thematically and summarised.

Key findings

- Respiratory outcomes were the most commonly researched health benefits among the eligible literature. Respiratory outcomes included asthma, COPD, chronic bronchitis, bronchodilator use, and upper and lower respiratory symptoms.
- Evidence for respiratory benefits due to air filtration was mixed. Tree species, urban form and type of pollutant included in the studies likely play a role in whether green space is beneficial or harmful, particularly in relation to respiratory health, due to allergenicity and concentration rather than filtering of air pollution.
- Perinatal and maternal outcomes are emerging topics of interest with respect to air filtration. Air filtration was associated with a range of beneficial outcomes, including birthweight, pre-term births, maternal blood glucose levels and congenital heart disease. Where mediation analysis was included in studies, the beneficial health effects were found to be only partially due to the air filtering capacity of green space. Other studies found a weak or no association, which may have been due to study design limitations.
- Fewer studies investigated air filtration and cardiovascular outcomes. These studies found that green space likely accounts for some, but not all, of the beneficial effect seen in cardiovascular outcomes associated with green space proximity.
- Eight research articles examined the economic impact on health from air filtration ecosystem services, 2 of which aligned with the SEEA or the SEEA EA accounting principles. Air filtration provided by vegetation led to substantial avoided health care costs in all cases. However, the amount varied depending on vegetation type, pollutant type and geographic location.

3.6 Mortality

The search produced 3 research papers and one review focusing on the link between air pollution removal and mortality (Chen 2020; James et al. 2016; Nowak et al. 2014; Nowak et al. 2018).

Using data from the United States-based National Nurses' Health Study, James et al. (2016) investigated the association between the amount of green space within a 250 m radius (within immediate access) and a 1,250 m radius (a 10–15 minute walk) of the participants' homes and the 8,604 non-accidental cause and cause-specific deaths that occurred among the study population between 2000–2008. After adjusting for potential confounders (including ethnicity, smoking status, weight), this study found an association between living in areas of higher amounts of vegetation and decreased mortality, with a 12% decrease in mortality for those living in areas with the highest quintile of cumulative average greenness compared with those living in areas with the lowest quintile. Mediation analysis to determine possible pathways explaining the association between green space (within a 250 m radius) and mortality indicated that PM2.5 air pollution explained 4.4% of the association. Results were similar for green space within a 1,250 m radius, though considerably lower than the findings for depression (determined by physician diagnosis, or antidepressant use), and social engagement, which accounted for 31% and 19% of the association, respectively. Physical activity accounted for 2.1% of the association. Therefore, while the cumulative benefits of living within areas of higher levels of green space were associated with decreased non-accidental causes of death, decreased air pollution is likely to be only partially responsible for the observed benefit.

In their study on the impacts of trees and forests on air quality in relation to human health across the United States, Nowak et al. (2014) estimated that these removed 17.4 million tonnes of pollution (NO_2, O_3, PM2.5, SO_2) in one year. This resulted in an estimated avoidance of greater than 850 incidences of all-cause mortality across the United States for that year. These estimates were based on aggregated and pooled estimates drawn from an open-source data program called the Benefits Mapping and Analysis Program (BenMAP) (US EPA 2022) (see Appendix C, Table C1 for a list of health conditions included in the data). A similar study by Nowak et al. (2018) estimated that urban forests in 86 cities in Canada were responsible for removing 16,500 tonnes of pollution (CO, NO_2, O_3, PM2.5, SO_2), resulting in greater than 30 avoided incidences of mortality in one year.

A review by Chen (2020) included 2 further studies on the impact of air pollution removal by vegetation on mortality. One study estimated that removal of PM2.5 by urban trees in New York reduced the incidence of mortality by 7.6 people per year (Nowak et al. 2013); the other, a United Kingdom based study, estimated that large woodland areas could reduce mortality by 5 to 7 cases per year through absorption of air pollution (Powe and Willis 2004).

3.7 Respiratory health

Of the literature eligible for inclusion, 14 articles included some focus on respiratory health (in relation to a range of ambient air pollutants) in conjunction with green space:

- 6 articles were reviews of the literature on health (with inclusion of respiratory health) (Chen 2020; Chiabai et al. 2018; Coutts and Hahn 2015; Kumar et al. 2019; Salmond et al. 2016; Wolf et al. 2020)
- one article was a review with causal criteria analysis (de Jesus Crespo and Fulford 2018)
- 7 articles presented research into the relationship between air filtration and health outcomes, including respiratory diseases such as COPD, rhinitis, bronchitis, asthma, respiratory hospitalisation and emergency department visits (Cochran et al. 2019; E Almeida et al. 2020; Feng and Astell-Burt 2017; Gopalakrishnan et al. 2018; Nowak et al. 2014; Nowak et al. 2018; Remme et al. 2015).

Of the 6 review articles, 4 reported some evidence supporting an association between air filtration, access to green space and favourable respiratory health outcomes (Chiabai et al. 2018; Coutts and Hahn 2015; Salmond et al. 2016; Wolf et al. 2020). This evidence included:

- an association between the type of green space and asthma hospitalisations: low-lying vegetation (such as gardens and lawns) resulted in fewer asthma-related hospitalisations when ambient air pollution levels were low, while higher standing vegetation (such as trees) resulted in fewer asthma-related hospitalisations when ambient air pollution levels were higher (Alcock et al. 2017 *in* Wolf et al. 2020)
- a strong relationship between increased mortality due to respiratory (and cardiovascular) disease and the loss of trees due to an emerald ash borer infestation in regions of eastern United States (Donovan et al. 2013 *in* Coutts and Hahn 2015). The review authors acknowledged that the mechanism for this could be due to a number of ecosystem services, but the link with respiratory mortality suggests it is related to a disruption in capacity to remove air pollution due to tree destruction (Coutts and Hahn 2015)
- lower odds of upper respiratory symptoms, asthma and COPD being associated with above average green space in the place of residence (Maas et al. 2009 *in* Chiabai et al. 2018)
- the mitigation of a small number of deaths and hospital admissions annually by non-urban forests in Great Britain, through the removal of PM10 and SO_2 ambient air pollution (Powe and Willis 2004 *in* Salmond et al. 2016).

However, each of these reviews highlighted that much of the available evidence on the impact of air filtration on respiratory health:

- was mixed (some found a reduction in illness, while others found an increase), or
- lacked evidence of the mechanisms by which air filtration systems improve respiratory health, or
- had correlations that were not statistically significant.

For example, Wolf et al. (2020) reviewed several studies in which there was no significant association between vegetation and asthma hospitalisations. Kumar et al. (2019) pointed out a lack of evidence for the mediating mechanism that links air filtration by vegetation with human health and highlighted this as a research gap.

In general, the authors of these reviews concluded that this variability in results is likely due to a number of location-specific factors, such as:

- the presence of allergenic tree species (which cause, rather than mitigate, respiratory illness), and person-level susceptibility to these species (Chiabai et al. 2018; Kumar et al. 2019; Wolf et al. 2020)
- the extent to which different types of vegetation can effectively remove particulate matter (for example, leaf surface area and type or location of the vegetation) (Salmond et al. 2016)
- the influence of the urban form on aspects such as air flow, which can underestimate the amount of air pollution deposited on leaf surfaces (Kumar et al. 2019; Salmond et al. 2016)
- the health of the trees and forests providing the ecosystem service, with trees under stress (due to climatic conditions or infestations) producing harmful VOCs (Salmond et al. 2016).

See Box 3.1 for more information on negative impacts of vegetation on human health.

Additionally, Coutts and Hahn (2015) state that while air filtration services can remove harmful air pollution, the benefits are limited because the rate of removal is well below the rate at which air pollution is produced, so it cannot obviate the need to reduce anthropogenic emissions at the source.

Box 3.1: Ecosystem disservices of vegetation

While vegetation can provide benefits in removing ambient air pollution, it can also increase it; in these circumstances, it is said to provide an 'ecosystem disservice'. Some of the features of plants that can result in decreased air quality include:

• emission of BVOCs: BVOCs can be converted to harmful ozone and PM2.5 (Chameides et al.1988; Hodan and Barnard 2004)

• allergenic tree species: pollen from some species can cause allergies in some people (Cariñanos and Casares-Porcel 2011)

• canopy density and design: the location of areas of vegetation may prevent air pollution from being dispersed by reducing air flow (Wolf et al. 2020). For example, air pollution can be trapped beneath the tree canopy, which, if located near the source of emissions, such as vehicles, can increase the levels of ambient air pollution in areas used by pedestrians (Gromke and Blocken 2015).

Ecosystem disservices of vegetation are important to human health as they result in increased exposure to ambient air pollution, which may, in turn, lead to increased burden of disease due to health conditions discussed in this section. Hence, to optimise health benefits, selecting the right trees for the right location (for example, non-allergenic trees near residential areas) needs to be carefully considered; it is also important to understand the impacts of street tree positioning and canopy on air flow dynamics and the exchange between clean and polluted air at the local level.

One review focused on the monetary valuation of vegetation on health. Overall, it found strong statistical evidence of monetary benefits from urban vegetation, derived in part from the ability to remove air pollution (Chen 2020). This review identified the work of Nowak et al. (2014) as being important in calculating monetary impacts; this is discussed in more detail in Section 3.11.

The majority of the eligible research articles examining respiratory health looked only at associations between air quality, green space and respiratory health. Only one (de Jesus Crespo and Fulford 2018) investigated a causal pathway between green space, air filtration and respiratory outcomes, while another sought to determine whether exposure to higher levels of green space may protect against childhood asthma by modifying the effect of nearby heavy traffic (Feng and Astell-Burt 2017).

de Jesus Crespo and Fulford (2018) applied causal criteria analysis to investigate whether there is enough evidence to infer causal links between green space, 'buffering' ecosystem services (such as air filtration provided by green space) and respiratory illness. The analysis involved examining the evidence firstly for a link between green space and the buffering ecosystem service of clean air, then for a link between clean air and respiratory illness, and finally for a link between green space and respiratory illness. The authors found that, while the evidence supported a link between the role of green space and clean air, the evidence for causality between clean air as a buffer against respiratory illness was inconsistent when using asthma as a response.

The authors concluded that this variability may be due to the choice of PM2.5 as an indicator of air pollution (whereas the relative concentration of oxidative stress-inducing particles might be a better indicator of likelihood to cause asthma) and seasonal variations – for example, greater exposure to indoor pollutants in winter (Walters et al. 1994) or altered pollutant diffusion patterns during winter (Zhen et al. 2013).

Hence, the evidence linking green space and respiratory illness was inconsistent, likely due to the inconsistent link between clean air and asthma, as well as allergies. Possible explanations for this include wind flow dynamics – which may result in re-suspension and concentration of air pollution due to the location and form of trees (Wania et al. 2012) – and production of allergenic pollen by certain tree species (Lovasi et al. 2013a) (see Box 3.1 for more detail). Therefore, the ability of green space to deliver positive respiratory outcomes depends on careful planning in selecting species and locating vegetation.

An Australian-based cross-sectional study by Feng and Astell-Burt (2017) investigated whether green space modified the association between asthma in children and traffic volume and neighbourhood safety. The authors used effect measure modification to determine the contribution of green space to childhood asthma through the proposed pathways of air pollution (as measured by traffic volume) and psychosocial means (as measured by the perceived safety of the local environment). Effect measure modification occurs when the association between 2 variables (for example, traffic and asthma) is modified, based on the level of another factor (in this case, the amount of green space in the residential area). Using this approach, the authors found that living in areas with greater amounts of green space modified the effect of heavy traffic on the prevalence of asthma in children. The odds of having asthma were higher among those living in high traffic areas with low amounts of green space (OR 1.87); for those living in high traffic areas with the highest level of green space, the odds of having asthma were significantly lower (OR 0.32). This study did not find a significant association between perceived neighbourhood safety and asthma risk, and different levels of green space. Therefore, these 2 findings suggest that the protective effect of green space on childhood asthma is more likely to be through the air filtration capacity of green space than through the proposed psychosocial mechanism of perceived neighbourhood safety.

In a study of the association between traffic air pollution, proximity to urban forest and the impact on respiratory health in children, E Almeida et al. (2020) determined that traffic-related NO_2 and PM10 was higher at points closer to heavily used roads, and lower at the point closer to an urban park with dense tree coverage, which provided a buffer from air pollution. They also found that, compared with symptom prevalence in children residing closer to the park, the prevalence of rhinitis and night-time dry cough or trouble breathing was significantly higher at locations that were 50 m and 900 m from the highway, and rhinitis prevalence was significantly higher at the location that was 900 m from the highway. The authors concluded that the presence of urban green space is an important mitigating factor, although their methods could not establish causality.

Four articles included research into the estimated monetary value of ecosystem services, including air pollution removal, and the effect on health, with reference to respiratory health (Gopalakrishnan et al. 2018; Nowak et al. 2014; Nowak et al. 2018; Remme et al. 2015). These studies reported the cost of the impact of a range of air pollution types on various health conditions and outcomes, including, but not limited to, respiratory conditions, such as:

- chronic bronchitis, respiratory hospital admissions, bronchodilator use, lower respiratory symptoms (Remme et al. 2015)
- acute respiratory conditions, emergency department and hospital admissions for respiratory conditions, asthma exacerbations, mortality, school and work loss days, upper and lower respiratory symptoms (Gopalakrishnan et al. 2018)

- acute bronchitis, acute respiratory symptoms, asthma exacerbations, respiratory hospital admissions, upper and lower respiratory symptoms (Nowak et al. 2014; Nowak et al. 2018).

These studies included the costs due to other health conditions and outcomes, such as cardiovascular conditions and overall mortality. See Section 3.11 for more detail.

3.8 Cardiovascular health

Many studies mention associations between green space and cardiovascular disease (such as heart disease and stroke), or between air pollution and cardiovascular disease. Fewer studies have examined the relationship between the filtration of air pollution by vegetation, and the impact of this on cardiovascular outcomes. The search returned 11 articles with some mention of cardiovascular and/or cerebrovascular disease. Of these:

- 4 were reviews (Chen 2020; Chiabai et al. 2018; Kumar et al. 2019; Salmond et al. 2016)
- one was a causal criteria analysis of reviewed literature (de Jesus Crespo and Fulford 2018)
- 6 were research articles (Gopalakrishnan et al. 2019; Nowak et al. 2014; Nowak et al. 2018; Remme et al. 2015; Shen and Lung 2016; Yang et al. 2019).

Of the reviews, only Chiabai et al. (2018) referred to research linking air purification, vegetation and cardiovascular health, referencing research by Hu et al. (2008), which found that the risk of stroke mortality was higher in areas of lower green space and higher air pollution levels. Chiabai et al. (2018), Kumar et al. (2019) and Salmond et al. (2016) all noted the lack of evidence of the mechanisms of vegetation on the reduction in cardiovascular health outcomes and highlighted this as a knowledge gap.

Three articles aimed to determine if a relationship between air filtration ecosystem services and cardiovascular health exists (de Jesus Crespo and Fulford 2018; Shen and Lung 2016; Yang et al. 2019).

Shen and Lung (2016) investigated the effects of green space structure (such as green patch size, fragmentation and nearest space) on mortality due to select cardiovascular conditions (hypertensive diseases, and aortic aneurysm and dissection). The authors used a form of structural equation modelling known as partial least squares modelling to determine the causal relationships between green space and cardiovascular mortality outcomes, and to estimate the extent to which the observed effects either were directly due to the green space type, or were mediated by air pollution (CO, nitric oxide (NO), PM10 and SO_2) and annual mean temperature. The results indicated that the largest patch percentage of green space was associated with decreased cardiovascular mortality through reduction of air pollution and temperature. Conversely, the more fragmented green space patches, and further distance to green space, were associated with increased mortality due to air pollution and temperature. The authors also modelled the individual effects of air pollution and temperature. This model showed that while both played a mediating role, air pollution played the greater role in the mediating effect of green space on cardiovascular mortality than temperature did. This suggested that green space provided both air filtration and local climate regulation, with air filtration contributing the greater mitigating effect on cardiovascular mortality outcomes.

de Jesus Crespo and Fulford (2018) performed a causal criteria analysis to investigate whether there is enough evidence to infer causal links between green space, 'buffering' ecosystem services (such as air filtration provided by green space) and cardiovascular disease. The authors examined the evidence firstly for a link between green space and the buffering ecosystem service of clean air, then for a link between clean air and cardiovascular disease and finally for a link between green space and cardiovascular disease. While the evidence supported a causal link between green space and clean air, the authors found that the evidence to support a link between clean air and cardiovascular disease was inconsistent. They hypothesised this could be due either to the use of different indicators for cardiovascular disease assessed in the various studies that informed the analysis, or to confounding by a range factors (such as demographics). They also noted that the 'inconsistent' finding was not equivalent to finding no evidence for the relationship, rather a potential artifact of the research design. In the final step of their causal criteria analysis, the authors found evidence to support the link between green space and cardiovascular disease. However, they could not eliminate the possibility that the benefits of green space on cardiovascular health were not due to the clean air buffering ecosystem service, but rather to other buffering ecosystem services – for example, physical activity or stress reduction (which would occur via recreational ecosystem services). The authors concluded that while clean air has a modest buffering role for cardiovascular disease, the contribution green space makes to this is likely to be minimal compared with other pollution reduction strategies.

Nowak et al. (2014) and Nowak et al. (2018) included measures of cardiovascular morbidity derived from the BenMAP tool for evaluating the economic impacts of air pollution removal on human health (see Section 3.11 for more information).

Blood pressure

Yang et al. (2019) investigated the mediating factors between community green space and blood pressure in a large sample (*n*=24,845) of adults living in China. The authors found that living in areas with increased levels of greenness was significantly associated with lower systolic blood pressure and decreased prevalence of hypertension, after adjusting for potential confounders (age, sex, ethnicity, income and area level gross domestic product). Specifically, systolic blood pressure was lower by 0.82 mmHg, and the odds of having hypertension were 5% lower, per Interquartile Range increase in greenness level within a 500 m residential buffer zone.

To determine whether this relationship between higher greenness exposure and lower systolic blood pressure could be explained by other factors, the authors performed mediation analysis (see Box 2.3) with air pollution (NO_2 and PM2.5), BMI and physical activity. This analysis revealed that NO_2 and PM2.5 mediated 14% and 16% of the association, respectively, while BMI mediated a greater proportion of the association, at 40%. However, physical activity was not found to be a mediating factor. This demonstrated that greater levels of greenness may favourably affect blood pressure by removing 2 common air pollutants, although other factors (such as BMI) also play an important role in the association.

3.9 Maternal and (non-respiratory) childhood outcomes

The theoretical assumption that birth outcomes are positively affected by reduced air pollution through exposure to green space or vegetation (Anabitarte et al. 2020) has prompted recent interest in exploring and quantifying these pathways. Of the literature selected for this review, 11 research articles and 1 review examined the evidence for air filtration services and maternal, perinatal and childhood outcomes. The most common outcome investigated was birthweight (Agay-Shay et al. 2019; Anabitarte et al. 2020; Chen 2020; Cusack et al. 2018; Dzhambov et al. 2019; Laurent et al. 2019; Lee et al. 2021), although pre-term births (Agay-Shay et al. 2019; Dzhambov et al. 2019; Sun et al. 2020), congenital heart defects (Nie et al. 2020), pre-eclampsia (Weber et al. 2021) and maternal glucose levels (Liao et al. 2019) were also examined.

A systematic review by Chen (2020) on the monetary valuation of the effect of nature in urban environments found that higher birthweight was associated with greater tree canopy in urban areas, and that a 10% increase of tree cover within 50 m of the maternal residence resulted in a lower risk of babies being born small for gestational age (that is, weighing less than the 10th percentile). However, the review did not determine the causal link between green space and birth outcomes and, specifically, the contribution of air pollution levels to these outcomes. As such it cannot be determined from this review whether air filtration services are associated with the observed health benefits.

Other authors sought to understand these mechanisms by including air pollution in their analyses of green space exposure and birth outcomes. Lee et al. (2021) investigated the effect of exposure to different levels of residential greenness during the first and third trimesters of pregnancy for women living in Taiwan. The authors found that exposure to green space reduced the risk of pre-term births (defined as a birth at less than 37 weeks gestation), and small-for-gestational age babies, and that these effects were mediated by PM2.5 and PM10 exposure. The authors concluded that, in the first trimester, around 5–19% of the benefits of exposure to green space on pre-term birth and small-for-gestational age was due to reduced particulate matter air pollution, and that this was even greater in the third trimester (15–37%).

Sun and others (2020) studied the effect of exposure to green space and the outcome of pre-term births in California in relation to exposure to NO_2, O_3 and PM2.5. After controlling for maternal age, race/ethnicity, education and median household income, the study found an association between exposure to green space and decreased risk of pre-term births. The results also suggested a link between green space, air pollution and birth outcomes – specifically, that decreased green space has worse effects on pre-term birth outcomes for women exposed to higher air pollution levels.

Another Californian-based study by Weber and others (2021) found that pre-eclampsia was correlated with lower exposure to green space, higher particulate matter exposure and living in higher poverty neighbourhoods.

In other evidence for the air filtering capacity of green space on birth outcomes, Nie et al. (2020) conducted a case-control study in 21 cities in southern China and found that exposure to greater amounts of green space before pregnancy and during the first trimester was associated with lower odds of congenital heart disease. Mediation analyses found that exposure to NO_2, PM1 (particulate matter less than 1 micron in diameter), PM2.5 and PM10 explained up to 52% of this association.

In their longitudinal study of all birth records in California between 2001 and 2008, Laurent et al. (2019) investigated the association between green space exposure during pregnancy and the outcome of low birthweight in full term births – and the potential influence of air pollution on that association. The authors measured green space exposure by NDVI within a 500 m radius of participants' residences (calculated for each trimester and for the entire pregnancy). Air pollution was determined by a range of indicators, including traffic-related particulate matter (PM2.5) and elemental carbon, and secondary pollutants (such as NO_2 and O_3). After adjusting for potential confounders (maternal age, race, level of education, mean household income, time of conception and length of gestation), the authors found that the risk of low birthweight at full term was highest in the area with the lowest amount of green space. Conversely, the risk was lowest in the area with the greatest amount of green space. The authors then performed causal mediation analyses (VanderWeele 2015) to examine the interaction between green space exposure during pregnancy, term low birthweight and air pollution to determine by how much air pollution exposure might explain the outcome. The results showed that the protective effect of residential green space exposure during pregnancy on term birthweight (by reducing PM2.5 and elemental carbon levels in the residential area) was 12% and 17%, respectively, although this was lower for the other components of air pollution tested. That is, up to 17% of the benefit supplied by green space during pregnancy, in terms of reduced risk of term low birthweight, is attributable to reductions in components of local air pollution. While this provides valuable quantitative information on the impact of green space on birth outcomes due to air pollution exposure, the authors acknowledged that it does not account for total effect, and that other mechanisms, such as local climate regulation, noise attenuation or physical activity could also be examined.

In a large cohort study of pregnant women in an urban region of China, Liao et al. (2019) explored the association between residential maternal green space exposure during pregnancy and maternal blood glucose measures – and the potential mediation effects of air pollution exposure and maternal physical activity – as possible mechanistic pathways for the association. After adjusting for potential confounders (demographic, socioeconomic, and personal characteristics such as overweight and obesity and exposure to passive smoking), pregnant women living in areas of greater green space were found to have lower blood glucose levels, and a lower risk of impaired glucose tolerance (IGT) and gestational diabetes mellitus (GDM) than those living in areas of the lowest amount of green space. Mediation analysis showed that reduced exposure to PM2.5 mediated 22% of the association between maternal residential green space exposure and maternal fasting glucose levels. However, the results for other measures of maternal glucose levels (IGT and GDM) were not significant.

Liao et al. (2019) also examined the potential mediating role of maternal physical activity on glucose measurements but did not find any significant mediating effect – although they suggest that this may be due in part to limitations with the measure of physical activity used in the study. As this study found that exposure to PM2.5 air pollution only partially mediated the effect of green space on maternal fasting glucose levels, other mechanisms should be explored for their potential contributions; the authors suggest that known associations between noise exposure and diabetes, and sleep quality and GDM make these potential candidates for further study.

In contrast, other studies found weak or no evidence for the air filtering effects of green space on birth outcomes. In examining the role of NO_2 exposure during pregnancy in mediating the effects of green space on birth outcomes, Anabitarte et al. (2020) found a negative direct effect of green space on birthweight with the average birthweight being lower for those living closer to green spaces than for those living further away – contrary to expectations based on previous findings. The authors postulated that their results may have differed from those of previous studies due to the level of greenness within which the study population lived being lower than that of those studies where a positive association was found. They also acknowledged that, had they included PM2.5 and PM10 measurements, their study may have produced different results, due to the known association of these pollutants with birth outcomes.

Another study looking at the effect of exposure to green space, ambient air pollution (NO_2) and traffic noise on birth outcomes in alpine areas of Austria and Italy was inconclusive; the authors reported that larger and more representative samples were needed to determine whether the effect was significant (Dzhambov et al. 2019).

Agay-Shay et al. (2019) included air pollution exposure in their mediation analysis in evaluating the relationship between maternal green space exposure and birth outcomes (birthweight, small-for-gestational age, and pre-term deliveries). They found that air pollution did not have a mediating effect.

Similarly, Cusack et al. (2018) found that controlling for ambient air pollution did not affect the association between maternal green space exposure and birthweight outcomes; the authors reported that this may have been due to the way in which the variables were measured, or that there was residual or unmeasured confounding.

One study focused on older school-aged children, and the effect of green space exposure on cognitive development over a 12-month period (Dadvand et al. 2015). This study showed that children in Barcelona, Spain, who were exposed to more green space within and around their school environments had better cognitive development over the study period than those exposed to less green space, and that air pollution mediated between 20–65% of the association. It should be noted that the measure of pollution used in the study was the level of indoor elemental carbon, as an indicator of nearby traffic-related air pollution, rather than the more commonly used measures of ambient particulate matter (PM2.5, PM10) or NO_2.

Despite the variable evidence for benefits of air filtration ecosystem services for perinatal and child health, it appears that more research is emerging, focusing on identifying causal pathways – due to the solid evidence supporting the negative impacts of ambient air pollution and the positive impacts of green space on birth outcomes. Specific local factors, such as vegetation type and location-specific morbidity rates, will need to be considered in future research to explain the differing outcomes.

3.10 Air filtration and mental health

The search strategy revealed one result for air filtration and mental health (Engemann et al. 2020b). Based on previous findings of an association between higher green space exposure and lower rates of schizophrenia (Engemann et al. 2018), Engemann et al. (2020b) sought to elucidate the potential mediating role of air pollution in the association between growing up in areas with different types of land cover (urban, near-natural green space, agricultural land and blue space) and the development of schizophrenia. The authors hypothesised that the type of land cover may lead to decreased rates of schizophrenia through mitigation of air pollution. To test for this, they adjusted for mean exposure to air pollution from birth to the 10th birthday.

In their main analysis, the authors found decreased risks of developing schizophrenia in those exposed to more natural environments during childhood. Exposure to blue space had the strongest effect on lowering the risk of developing schizophrenia (HR 0.64), followed by agricultural land cover (HR 0.69) and near natural green space (HR 0.74). After adjusting for indicators of air pollution, the effect size for developing schizophrenia changed the most for near natural green space (from HR 0.74 in the main analysis to HR 0.81 when adjusting for air pollution), while the least change was seen for blue space (from 0.64 in the main analysis to 0.66 after adjusting for air pollution). Furthermore, mediation analysis revealed that near-natural green space had the strongest mediating effect on air pollution (44% compared with 15% for agricultural land and 7.1% for blue space) and that vegetation density explained part of this association (26% compared with 3.9% for agricultural land and 2.9% for blue space). These results suggested that growing up in near-natural green space provided a protective effect against schizophrenia, in part through exposure to vegetation, but that the mitigating impact of blue space and agricultural land is less pronounced. The authors concluded that exposure to near-natural environments during childhood may play an important protective role against schizophrenia. Although this large population-based study using longitudinal data provided useful information on residential land-type and air pollution exposures during childhood and mental health outcomes, conclusions are limited to residential exposures (rather than actual exposures, which may vary with movement between home and other environments on a regular basis). Furthermore, the study could not account for actual use of these environments and how this may influence mental health.

3.11 Economic impact and health

Understanding the cost impact of the relationship between air filtration ecosystem services and health is important for policy and planning decisions. Eight research articles selected for this review included a focus on monetary valuation of the impact of air filtration service provision on human health (Capotorti et al. 2019; Endreny et al. 2017; Gopalakrishnan et al. 2018; Nowak et al. 2014; Nowak et al. 2018; Paulin et al. 2020; Remme et al. 2015; Tapsuwan et al. 2021).

These studies used modelling techniques to assess the amount of vegetation coverage, the amount of air pollution removed (by pollutant type), and the economic impact of avoided health care costs. To do this, the majority of the studies used the BenMAP and / or i-Tree Eco software packages, which are designed for use in calculating avoided costs to human health due to reduced air pollution from vegetation (see Box 3.2). A minority used other data collection methods for their model inputs (for example, Paulin et al. 2020 used a range of national data sets to derive their models). Only 2 papers specifically referred to the application of the SEEA framework for their valuation approach (Remme et al. 2015; Tapsuwan et al. 2021). Table 3.1 summarises these 8 research articles and their findings, with a selection of the studies outlined in more detail in this subsection.

Box 3.2: Tools for quantifying air filtration ecosystem services and health

i-Tree

Developed by the United States Department of Agriculture Forest Service, i-Tree is a suite of computer programs designed to assess the potential of ecosystem services. Using input data from over 40 countries on biomass, leaf area, tree species, weather, upper air, air quality and geospatial-related data, the software quantifies urban forest structure, street trees and other vegetation types and the ecosystem services they provide. Ecosystem service estimates include carbon storage and sequestration, air pollution removal, human health effects associated with air pollution removal, heating and cooling energy savings in houses, and stormwater run-off avoided (Tan et al. 2021).

Environmental Benefits Mapping and Analysis Program

The BenMAP is an open-source computer program that calculates the number and economic value of deaths and illnesses related to air pollution (US EPA 2022). Developed by the United States Environmental Protection Agency, it consolidates human medical records and air quality measurements from across the United States (Tan et al. 2021). A range of human health metrics can be analysed using the BenMAP; they include acute respiratory symptoms, asthma exacerbations, acute myocardial infarction, acute/chronic bronchitis as well as hospital admissions, emergency visits, mortality and school and work days lost due to the health impacts of air pollution.

(continued)

Box 3.2 (continued): tools for quanitifying air filtration ecosystem serives and health

The avoided damage cost is a method used to estimate the value of an ecosystem service. It is the cost of the damage that would occur if that ecosystem service was absent. The BenMAP calculates the economic value of air quality change using 2 metrics: 'cost of illness' and 'willingness to pay'. The cost of illness metric estimates the expense to the individual for hospital admissions, emergency department visits and other health outcomes related to air pollution. The metric takes into account medical experiences and lost work. The willingness metric accounts for direct costs noted in the cost of illness metric, as well as the value that individuals place on pain, suffering and loss of satisfaction and leisure time (US EPA 2022).

How these tools interact

BenMAP modelling can be integrated into i-Tree programs to estimate health impacts due to changes in pollution concentration.

The economic impact of air filtration services on health varied, depending on the location and type of vegetation being studied. For example, Nowak et al. (2014) modelled costs across the 48 adjoining states of the United States, including rural and urban areas, for 2010. Using the BenMAP (US EPA 2022), the authors evaluated the health impact and monetary value attached to changes in NO_2, O_3, PM2.5 and SO_2 levels. The health effects investigated included a range of respiratory symptoms (bronchitis, acute respiratory symptoms, asthma exacerbations, bronchitis), cardiovascular conditions (non-fatal myocardial infarction) and all-cause mortality, as well as hospital admissions, work loss days and school days missed due to these conditions. For a full list of conditions included, see Appendix C, Table C1.

Overall, Nowak et al. (2014) found that, while the average percentage of air quality improvement due to vegetation was less than 1%, this still represented a substantial economic benefit – an estimated average value of US$6.8 billion. The greatest amount of pollution removal was in rural areas, but the highest cost saving was in the more densely populated urban areas. The authors also found that monetary values were highest for O_3 and PM2.5 pollution, due to their impact on human mortality. They concluded that urban trees were of particular importance to human health, as they affect more people. For more information on the economic impact of air filtration on health from this study, see Table 3.1.

In a similar study of urban forests in Canada in 2010, Nowak et al. (2018) used the BenMAP (US EPA 2022) to investigate health incidence data and the monetary value of CO, NO_2, O_3, PM2.5 and SO_2, in conjunction with i-Tree to calculate the pollutant removal and changes in pollution concentrations. The total estimated value of air pollution removal provided by urban trees for human health was C$227.2 million (for the study year), with most of that value being linked to the removal of O_3 and PM2.5. The authors noted that the health benefits obtained depend not only on the amount of pollution removed by trees, but also on the local population density. Areas with lower population density result in lower values for avoided costs, as there are fewer people to receive the ecosystem service benefit. See Table 3.1 for more information on these health benefits.

Remme et al. (2015) conducted a test case for accounting for ecosystem services, based in the Limburg province in the Netherlands. The authors sought to value ecosystem services using an approach that aligned with the United Nations accounting standards (System of National Accounts) (United Nations et al. 2009), as proposed by the SEEA Experimental Ecosystem Accounting guidelines (United Nations 2014). The ecosystem service of 'air quality regulation' (equivalent to air filtration) was included among the ecosystem services modelled and valued in the test case. The authors employed the avoided damage costs method (that is, the cost that would have occurred if the ecosystem service of air filtration had not been present), based on health costs due to air pollution. Specifically, they evaluated the impact of PM10 removal by forests on the following outcome measures:

- work loss days
- new bronchitis cases
- respiratory hospital admissions
- cardiac hospital admissions
- medication/bronchodilator use (for adults and for children)
- lower respiratory symptoms (for adults and for children).

The authors applied a value of €8 per person per avoided PM10 increase for all the above categories combined, based on the findings of previous studies (Preiss et al. 2008; RIVM 2012). Using land cover maps to identify forest areas, data on PM10 concentrations and population density data for the area of Limburg province, the authors estimated a total monetary value of up to €2.7 million for the ecosystem service of air filtration for that region. The analysis revealed that the highest values of avoided costs occurred in more densely populated, highly forested areas. Lower values occurred in areas of low population density and high forestation, and in areas with high population density and low forestation. This pattern was in line with the findings of Nowak et al. (2014) and Nowak et al. (2018).

Tapsuwan et al. (2021) also sought to apply the SEEA framework to calculate the benefits of air filtration. This Australian-based study estimated the health economic benefits of air pollution removal (O_3, CO, NO_2 and PM2.5) by trees in the Australian Capital Territory. The authors estimated that public forests in the territory in 2018 removed 154 tonnes of these 4 pollutants, with associated health expenditure savings of A$863,382 for that year (based on i-Tree eco-modelling and the cost of combined health effects from the BenMAP). This equates to a value of A$1.12 per tree for the study year (2018) in air pollution removal services alone. It should be noted that this was one of only 2 articles (along with Remme et al. 2015) from the search strategy that mentioned applying the SEEA framework to calculate the benefits of air filtration ecosystem services to human health.

Overall, these research studies found economic benefits associated with health impacts due to vegetation coverage – although the amount varied depending on vegetation type, pollutant type and location. The results, including health conditions studied, are summarised in Table 3.1. Due to the different methods used for these studies, the results from each cannot be directly compared.

Table 3.1: Summary of economic impacts and health

Reference	Study description	Air pollutants included in study	Estimated human health value (average)	Health outcomes	Air pollutant/s removal of greatest value
Capotorti et al. 2019	Rome, Italy, urban, 'green infrastructure' (natural and semi-natural areas, e.g. urban forest, coniferous and broad-leafed forest, natural grasslands, shrubs)	PM10	€40,700 – 130,200	Avoided costs for damages to human health, due to PM10 removal	n.a.
Endreney et al. 2017	Global, 10 'megacities', metropolitan	NO_2, O_3, PM2.5, PM10, SO_2	US$482 million	Not stated (i-Tree Eco, BenMAP incidences used for calculations)	PM2.5
Gopalakrishnan et al. 2018	United States, grasslands and shrublands	NO_2, O_3, PM2.5, PM10, SO_2	US$175 million (grasslands) US$93 million (shrublands)	Avoided incidences of asthma exacerbations: • 522–10,900 incidences (grasslands) • 347–9,040 incidences (shrublands) Avoided incidences of acute respiratory symptoms: • 56–14,500 (grasslands) • 37–8,420 (shrublands)	O_3, PM2.5
Nowak et al. 2014	United States, trees and forests	NO_2, O_3, PM2.5, SO_2	US$6.8 billion	Avoided incidences of selected[(a)] health outcomes due to removal of PM2.5: • 57 incidences of mortality • 168,701 incidences of acute respiratory symptoms • 137,298 incidences of asthma exacerbation • 203 emergency department visits • 71 cardiovascular hospital admissions • 28,815 lost work days	O_3, PM2.5

(continued)

Table 3.1 (continued): Summary of economic impacts and health

Reference	Study description	Air pollutants included in study	Estimated human health value (average)	Health outcomes	Air pollutant/s removal of greatest value
Nowak et al. 2018	Canada, 86 cities, urban forests	NO_2, O_3, PM2.5, SO_2	C$227.2 million	Avoided incidences of selected[(b)] health outcomes due to removal of all studied air pollutants combined: • 30 incidences of mortality • 21,916 incidences of acute respiratory symptoms • 16,539 incidences of asthma exacerbation • 25 emergency department visits • 2.7 cardiovascular hospital admissions • 1,168 lost work days • 4,586 lost school days	O_3, PM2.5
Paulin et al. 2020	Amsterdam, the Netherlands, mixed urban	PM10	€77 million	Reduced health costs due to PM10 removal	n.a.
Remme et al. 2015	Limburg province, the Netherlands, mixed (agriculture, nature, urban)	PM10	€2 million	Total avoided air pollution-related health costs due to PM10 removal, for combined: • bronchitis • respiratory hospital admissions • cardiac hospital admissions • bronchodilator use • lower respiratory symptoms • work loss days	n.a.
Tapsuwan et al. 2021	Australian Capital Territory, Australia, urban forests	NO_2, O_3, PM2.5, SO_2,	A$863,383	Avoided health expenditure	n.a.

n.a. = not applicable (indicates where the research did not state the individual contribution of each pollutant to the overall value of removal).

(a) For a complete list of adverse health effects by air pollutant type, see Table 4 in Nowak et al. 2014.

(b) For a complete list of adverse health effects, see Table 3 in Nowak et al. 2018.

3.12 Grey literature

International case study 1

A report published by the Wageningen University on behalf of the Ministry of Agriculture, Nature and Food Quality, Netherlands (Horlings et al. 2020) showed the first results of applying a monetary valuation of ecosystem services and ecosystem assets using the SEEA EA framework. The study estimated the value of 10 ecosystem services for the Netherlands and included air filtration. To value air filtration, an avoided damage cost was used (see Box 3.3), with PM2.5 captured by forests and other vegetation as the biophysical indicator. Using 3 measures, the study modelled data on ambient PM2.5 concentrations, forests and other vegetation cover with population size.

Box 3.3: Avoided damage costs

The avoided damage cost is a method used to estimate the value of an ecosystem service. It is the cost of the damage that would occur if that ecosystem service was absent.

The 3 measures used to apply monetary value of avoided damage costs to air filtration for households in the Netherlands were:

- avoided health costs
- value of a statistical life year (mean VOLY) to measure avoided health costs and avoided costs of mortality
- maximum societal revenue VOLY (MSR VOLY) to measure avoided health effects and avoided mortality if there were a 'market' for clean air.

The study found that the estimated reduced damage cost for avoided air pollution at the national scale for the Netherlands for 2015 ranged from €42.1 million (avoided health costs), to €85.8M (MSR VOLY) and €175.3M (mean VOLY). Deciduous forests were found to have the most benefit in reducing health and mortality costs. The study noted that trends over time for the ecosystem service were difficult to capture due to the changing nature of external factors. For instance, yearly trends have shown lower levels of PM2.5 concentration recorded in the Netherlands and, as a result, total avoided morbidity and mortality damage costs have decreased.

International case study 2

A study from the United Kingdom's Office of National Statistics (Jones et al. 2017) explored the role of vegetation in air pollution removal across the United Kingdom, and the benefits provided to human health through reductions in exposure. The study presented 2 accounts:

- a national United Kingdom account for air pollution removal by broad habitat types
- a cross-cutting urban account for Great Britain, showing air pollution removal by urban green space: woodland, grassland and urban blue space (freshwater/saltwater).

The study calculated air pollution removal with damage costs per unit exposure at the local authority level for a range of avoided health outcomes:

- respiratory hospital admissions
- cardiovascular hospital admissions

- loss of life years (long-term exposure effects from NO_2 and PM2.5)
- deaths (short-term exposure effects from O_3).

The study estimated that, in 2015, woodlands, plants, grasslands and other United Kingdom vegetation removed 1.3 billion kg of air pollutants. This was estimated to have saved the United Kingdom around £1 billion in avoided health damage costs. The study estimated 5,800 fewer respiratory hospital admissions, 1,300 fewer cardiovascular hospital admissions, 27,800 fewer life years lost and 1,900 fewer premature deaths in 2015 as result of nature's providing this service. Similar to the Netherlands account, pollutant concentrations were the major driver of change in the quantity of service provided – with pollution concentration found to have declined over time; with less pollution for the vegetation to remove, less of a service was required.

3.13 Gaps and limitations

Australian-specific studies

While the literature included in this review revealed strong associations between air filtration services and human health, there were some notable omissions.

- The academic literature search strategy returned only 2 papers specific to the Australian context (Feng and Astell-Burt 2017; Tapsuwan et al. 2021), even when additional searches including the terms 'Australia' or 'Australian' were conducted.
- An extensive search of the grey literature failed to find any material specific to Australia. This may have been due to limitations of the search strategy, or to research of air filtration and human health not being prioritised in Australia due to the country's generally good air quality (Paton-Walsh et al. 2019). Regardless, with Australia's predicted increased urbanisation (ABS 2022) – and changes in environmental conditions likely leading to greater frequency of events such as extreme bushfires (Abram et al. 2021) – the contribution of air filtration ecosystem services will have an important role in protecting human health, particularly within urban areas of Australia.

Contribution of blue spaces to air filtration

The chosen search methodology revealed a limited amount of literature focused on the contribution of blue spaces to air filtration, despite evidence that they can contribute to better air quality through decreasing concentrations of PM2.5 and PM10 (Georgiou et al. 2021; Paulin et al. 2020). The majority of studies focused solely on the contribution of vegetation (mostly as measured by NDVI) to air filtration, while others explicitly excluded bodies of water from their analyses (Dzhambov et al. 2019; Sun et al. 2020) – thereby overlooking the potential of all parts of the landscape to remove air pollution, and whether or not this would have additionally benefited human health.

Only 4 studies considered blue space:

- Anabitarte et al. (2020) performed a secondary analysis on a sub-sample of their study population to test for the effect of green or blue space on pregnancy outcomes by adding blue space as an additional exposure variable. The results were largely the same as those found in the main analysis – that is, with just green space as the exposure variable (other than a marginally significant effect of green space on birthweight).
- Engemann et al. (2020b) found an association between growing up surrounded by agricultural land, near-natural green space and blue space and lower rates of developing

schizophrenia. However, the analysis showed that blue space had only a minimal mitigating effect on air pollution, compared with densely vegetated areas.

- In defining green space for their causal criteria analysis, de Jesus Crespo and Fulford (2018:2) noted that this included 'urban trees, green roofs and wetlands'. However, the authors did not look at the contribution of each of these elements separately.
- Although Paulin et al. (2020) discussed the air filtration capacity of vegetation in their research, the methodology used to determine green space did not differentiate between vegetation and water. The authors noted the capacity for blue space to remove particulate matter but stated that methods for validating the retention of PM10 by vegetation and water would be too time consuming and expensive to conduct.

Air filtration and mental health

The literature search returned just one result on the mental health impacts of air filtration, relating to the association between green and blue space exposure during childhood and the development of schizophrenia (Engemann et al. 2020b). Including the term 'mental health' (or other permutations relating to mental or psychiatric conditions) may have returned a greater number of relevant articles. However, this outcome may also be because links between mental health, air pollution and green space are a very recent area of research and are still under investigation.

Several recent reviews have highlighted that, despite some evidence of an association between air pollution and a range of psychiatric and mental health conditions, the evidence is contradictory and inconclusive, and that more research is required (Gladka et al. 2018; Hahad et al. 2020; Ventriglio et al. 2021). Furthermore, the role of green space (and blue space) on mental health is uncertain. A review by Gascon et al. (2015) found that evidence for the beneficial impacts of green and blue space on mental health was inconclusive, and that further research is required to determine the relationship and underlying mechanisms.

Nonetheless, there is emerging evidence of increased risk of certain psychiatric illnesses associated with exposure to air pollution. For example, Newbury et al. (2021) found that exposure to residential air pollution was associated with increased use of mental health care services by people with a recent diagnosis of psychotic and mood disorders. The authors proposed that air pollution mitigation strategies had the potential to reduce associated health care costs. While these findings were based on the assumption of a causal pathway between air pollution and mental health – and do not determine the mechanism of the relationship – they do contribute to the emerging body of evidence in this area. It is therefore likely that, as well as the health benefits listed above, there may be other evidence soon to support the role of air filtration services in improving mental health.

4 Local climate regulation

4.1 What is local climate?

The term 'local climate' (sometimes known as mesoclimate) refers to the climate of relatively small geographic areas, such as neighbourhoods, small wooded areas, or zones within cities. The local climate is affected by the physical characteristics of the immediate area (such as vegetation cover, hills and water bodies). Local climates are not necessarily representative of climates across regions as a whole and can differ from 'macroclimates' (the climate of a whole region or country).

Local climates are affected and regulated by a range of factors, such as the presence and density of green space, blue space and urban heat islands.

4.2 Green space, blue space and local climate

In many local climates, particularly urban areas, heat is a key concern for both environmental health and human health. The cooling effect of urban vegetation and blue space is well established (Gunarwardena et al. 2017). On average, vegetated urban parks are estimated to be 0.94 degrees Celsius cooler during the day than their surrounding built or non-green environment (Bowler et al. 2010b). Urban blue spaces provide a similar cooling effect when compared with a rural reference site (Volker et al. 2013). The distribution and extent to which these cooling effects extend through space is not yet well understood (Gunawardena et al. 2017).

Green space mitigates excess heat through solar shading, modification of wind flow, and evapotranspiration. Solar shading from vegetation can block the sunlight to buildings and lead to reduced ground and wall surface temperatures. Urban plants and trees can also cool the climate by modifying wind flow (Gunawardena et al. 2017). Evapotranspiration is the process of heat transfer from the urban surface to the atmosphere via evaporation of water and transpiration from vegetation (Gunawardena et al. 2017; Volker et al. 2013). Increasing evapotranspiration can mitigate increased urban temperatures by restoring the urban energy balance.

Blue space mitigates excess heat in a similar manner to green space, as it provides evapotranspiration and cooling of surrounding air through evaporation and convection (Spronken-Smith et al. 2000).

Because of their cooling potential, increasing the proportion of green and blue space has been considered a potential mitigation strategy against urban heat islands and extreme heat (Gunawardena et al. 2017). In many cities (such as Los Angeles, California; Phoenix, Arizona; Chicago, Illinois; and Berlin, Germany, among others), tree planting initiatives now exist for this very reason (Jenerette et al. 2011).

Alongside their cooling potential, a lack of green space and blue space is linked to increased heat. Impervious surfaces (which include hard surfaces common in urban environments, such as rooftops, pavements and roads) are often examined in research as inverse measures of green space. Impervious surfaces have several negative effects on the local climate, including increased air temperatures, increased urban heat island effects, and reductions in air and water quality (Wu et al. 2014). For example, extreme heat and the intensity, size and distribution of urban heat islands have been linked to increases in impervious surfaces and reductions in urban green space (Hua et al. 2020). Without thoughtful urban planning, increasing urban densification is likely to exacerbate the urban heat island effect: taking up more land for private buildings decreases private green space and the tree canopy, and increases impervious surfaces (Saunders et al. 2020).

4.3 What is the urban heat island effect?

First observed in London in 1833, the urban heat island (UHI) effect is where temperatures in urban areas are higher than in rural areas (Heaviside et al. 2017). When measured against a reference point, such as a surrounding rural area, cities and urban areas are, on average, 2 to 4 degrees Celsius higher in temperature, although more extreme cases of the UHI effect have been observed (Bohnenstengel et al. 2011). The UHI effect tends to be proportional to population size; hence, more populated cities show a more intense UHI effect (Heaviside et al. 2017).

The UHI effect occurs for several reasons but is largely due to modification of land surfaces. Common surfaces in urban areas such as asphalt, bricks and concrete tend to absorb energy from the sun during the day, which is then slowly released into the air as heat, most often at night; this leads to stronger UHI effects at night than during the day. The general lack of vegetation, industrial heat output, household heating, energy use from vehicles, and lack of moisture, all further contribute to increased heat in urban areas compared with reference areas (Heaviside et al. 2017).

Temperature measurements derived from satellite imaging and/or ground-based collection points such as airport weather monitoring stations (see Box 4.1) are commonly used to determine the UHI effect.

Box 4.1: How is the urban heat island effect measured?

Measurements of temperature (and UHIs) can be distinguished based on whether they are ground-based or satellite-based, with strengths and weaknesses for both methods.

Ground observations: fixed or mobile?

Ground observations examine air temperature from within a city or region, typically from a single location such as an airport or weather monitoring station. Because these measurements are taken from fixed locations, they are less precise in capturing variation in temperature across regions. However, these limitations can be overcome by using mobile surveys.

Ground-based measures are likely to be more relevant for human health because they better capture human exposure to temperature. This is because ground-based measures read the ambient air temperature and, when combined with measures of humidity, reflect how temperature is actually perceived (‘apparent’ temperature).

Ground-based observations are also better at capturing temperature at night, when the UHI effect tends to be strongest.

Satellite or remotely sensed observations

Satellite-based imagery provides measures of land surface temperature, sometimes described as the ‘skin’ or surface temperature of the region. While land surface temperature measurements are arguably less relevant for human health (compared with air temperature), they have been commonly used in assessing UHIs.

(continued)

Box 4.1 (continued): How is the urban health island effect measured?

Satellite methods offer an advantage over ground-based methods because they can indicate how temperatures vary across a city or region. They provide greater precision in measuring:

• spatial variations in temperature across an area

• variations in the land surface itself.

Measurements of land surface temperature can be used in epidemiological studies of human health because they are correlated with ground-based air measurements within the same measurement area. Some researchers have used the term 'surface Urban Heat Island' to refer to UHIs that are measured through land surface temperature.

Surface temperature data from satellites also provide information on heat risk from the UHI that might vary with other geographic risk factors. For example, differences in surface temperature between neighbourhoods might point to risk factors for heat, such as socioeconomic group.

Sources: Heaviside et al. 2017; Marando et al. 2019; Mirzaei 2015; Venter et al. 2020; Zanobetti et al. 2013.

4.4 Non-optimal temperature and human health

The relationship between human health and non-optimal temperature – both cold and heat – is well established. Estimates published in 2015 from 74 million deaths across the United Kingdom and the United States suggested that 7.3% of all deaths were associated with cold temperatures (Gasparrini et al. 2015). More recent estimates taken from death data across 43 countries suggest that 8.5% of all deaths are associated with cold temperatures globally, equating to 67 cold-related excess deaths per 100,000 people (Zhao et al. 2021).

The most recent estimates suggest that 489,075 heat-related excess deaths occurred globally between 2000 and 2019, equating to 0.9% of all deaths and 7 heat-related excess deaths per 100,000 people (Zhao et al. 2021).

While there are more deaths globally related to cold than to heat, recent evidence suggests that the majority of temperature-related deaths in Australia may, in fact, be caused by heat – and that official records may have substantially underestimated the association between heat and mortality (Longden et al. 2020). The relative risk of mortality due to excess heat in Australia has been estimated by an early study at 1.06 – that is, the risk of mortality is increased by 6.0% during periods of excess heat (Guo et al. 2014). More recently, in Australia and New Zealand, 2,640 excess deaths were associated with heat, accounting for 1.5% of all excess deaths, or 10 heat-related deaths per 100,000 people (Zhao et al. 2021).

Across Australian capital cities, one study reported that about 7.26 deaths per 100,000 people were attributable to extreme heat between 2001 and 2015 (Longden 2018), with estimates of:

- 1,132 deaths due to heat and 151 deaths due to extreme heat in Melbourne
- 736 deaths due to heat and 32 deaths due to extreme heat in Sydney
- 406 deaths due to heat and 144 deaths due to extreme heat in Adelaide
- 478 deaths due to heat and 54 deaths due to extreme heat in Perth
- 220 deaths due to heat and no deaths due to extreme heat in Brisbane.

The relationship between heat and human health is underpinned by several pathways. Increased temperature stresses the human body's capacity to regulate its own temperature (thermoregulation). In turn, human physiology is placed under increasing demands to remain cool (Shahmohamadi et al. 2011). This can exacerbate pre-existing chronic conditions and can lead to heat-stress related injury. For example, heat stroke can occur if the body's temperature rises above 41 degrees Celsius, resulting in dizziness, fever, fainting, delirium, coma and death (Shahmohamadi et al. 2011). Exposure to cold similarly pressures thermoregulation but, in the case of cold temperatures, the body loses heat faster than it is produced, which can lead to hypothermia. Similar to excess heat, this can exacerbate pre-existing chronic conditions or lead to death.

4.5 What is the cost of heat mortality?

The economic cost of the human health impacts of climate change and heat are substantial. Climate-related events have been estimated to account for about US$14 billion from health costs and lives lost in the United States (Knowlton et al. 2011). Future estimates have placed the net cost associated with mortality incurred through climate change and the UHI effect at up to €17.6 billion (Botzen et al. 2020). Australian data are sparse but suggest there has been up to A$1.5 million in savings due to avoided mortality through various UHI mitigation strategies in the city of Melbourne (Whiteoak and Saiger 2019).

Estimates have also been derived from the cost savings associated with excess heat and other environmental exposures, based on the Value of Statistical Life method, assuming compliance with international exposure recommendations for physical activity, air pollution, noise, heat, and access to green space (Mueller et al. 2017). These authors estimated an average of 360 days of life gained if international exposure recommendations were met in Barcelona, Spain, equating to €9.3 billion saved annually. About €0.4 billion were estimated to be saved with improved access to green space, and €1.2 billion with decreases in cooling of temperatures by 4 degrees Celsius.

4.6 What is 'local-climate regulation'?

In the SEEA EA framework, the term 'local-climate regulation' refers to '*the ecosystem contributions to the regulation of ambient atmospheric conditions (including micro and mesoscale climates) through the presence of vegetation that improves the living conditions for people and supports economic production*' (UN et al. 2021:132).

These constitute a 'regulating and maintenance service' – that is, to regulate and maintain biological processes and influences on climate, thus helping to maintain environmental conditions beneficial to individuals and society.

Ecosystems provide local-climate regulation in a variety of ways, most notably through the regulation of ambient temperature and mitigation of the 'urban heat island effect'. Research has examined 'green space' and 'blue space' as key environmental characteristics that may achieve this goal.

4.7 Overview of the literature

Forty studies and 11 reviews relevant to human health and local climate (temperature) regulation of ecosystems (green/blue space) were identified. The articles covered a broad range of health outcomes, environmental exposures, study designs, locations and spatial scales, and the studies were conducted over several countries and/or continents, including

Australia, North America, Europe, Asia and Africa. Key characteristics of the eligible studies, including study type, location, setting/scale, sample size, environmental exposure and health outcome, are presented in Appendix C.

Only one study estimated monetary valuations in relation to health outcomes derived from ecosystem services (Sinha et al. 2021). However, a number were identified that reported either attributable fractions or attributable numbers, or provided estimates of avoided deaths based on green/blue space. Another 2 studies were identified that reported attributable numbers in relation to avoided morbidities. Although they do not assign an economic value, attributable fractions and numbers can be useful for applying economic estimates.

The following overview organises findings primarily by health outcome, before detailing the findings of economic impacts (avoided costs and avoided deaths), grey literature, and gaps and limitations of the included articles.

Key findings

- In general, the findings suggest a protective effect of green/blue space on the association between human health and increases in temperature, more so than for mitigation from cold temperatures.
- The degree to which a causal pathway can be reliably established between health outcomes and local climate ecosystem services through local climate regulation is limited. Furthermore, methodological differences – for example, in the measurements used between studies – further limit the degree to which conclusions can be reached from the current body of literature.
- All-cause mortality was the most commonly studied health outcome in relation to local climate regulation and, overall, the evidence supports a role of local climate regulation in reducing all-cause mortality. Green space, impervious surface, and population density ratios determine the size of the impact of local climate regulation on all-cause mortality and reduced deaths.
- A range of other health outcomes, including those related to cardiovascular health, respiratory health, diabetes and general and mental health, have been investigated in relation to local climate regulation. However, the evidence for the role of local climate regulation in providing health benefits from these studies is more varied: some studies found a protective effect and others, a negligible effect.
- There was limited evidence for health economic benefits of local climate regulation, with only one study evaluating the monetary benefits of local climate regulation from reduced mortality. This study calculated that increases in tree coverage would potentially result in considerable economic value due to avoided deaths. Furthermore, the monetary benefits from reducing heat were far greater than previous estimates from air filtration ecosystem services.

4.8 All-cause mortality

Six review papers and 21 studies were identified as relevant for all-cause mortality as a primary health outcome in relation to green/blue space and local climate cooling.

Reviews in this area suggest there is good evidence for a relationship between all-cause mortality and green/blue space but presented limited evidence that this effect occurs through the ecosystem service of local climate regulation.

Gascon et al. (2016) reviewed the association between exposure to residential green space and mortality in adults, concluding that there was moderate evidence for a link between green space and all-cause mortality. However, the review included only 2 studies where heat-related mortality was examined (Harlan et al. 2013; Uejio et al. 2011), and neither of these provided direct evidence of mitigation of temperature-related effects by green space.

Rojas-Ruedua et al. (2019) and Kua et al. (2021) conducted systematic reviews and meta-analyses on research examining the relationship between green space and all-cause mortality. According to these reviews, with every 0.1 NDVI unit increase in surrounding greenness, rates of all-cause mortality were estimated to fall by 3–4%. The former review reported that none of the included studies considered heat island effects (Rojas-Ruedua et al. 2019); the latter included 3 studies that examined the relevant environmental exposures (green/blue space and temperature) and health outcomes (Dang et al. 2018; He et al. 2020; Son et al. 2016) and concluded that the causal pathways were tenuous (Kua et al. 2021).

The review by Kolokotsma et al. (2020) highlighted 2 case studies as evidence for an effect of green space and temperature on mortality (Chen et al. 2014; Vanos et al. n.d.). The authors noted that these studies provided evidence that decreasing air temperatures during heat events through vegetation lead to reductions in mortality.

Two review papers were identified that were relevant to blue space:

- In a systematic review and meta-analysis of studies examining the relationship between blue space and human health, Smith et al. (2021) reported that proximity to blue space reduced the risk of all-cause mortality by about 1%. However, none of the studies used for this estimate shed light on the mechanism underlying this association. Therefore, it is not clear the extent to which these results can be attributed to a local climate regulating effect of blue space.
- White et al. (2020) reported that there was good evidence for positive health outcomes associated with access and exposure to blue space and suggested that mitigation of the UHI effect is one potential pathway by which these health benefits might be derived. However, these authors cited only a single study in support of such an effect (Burkart et al. 2016).

Of the research-based articles, all-cause mortality was the most commonly identified health outcome. Overall, the majority of these studies support that green/blue space has an effect on all-cause mortality through the regulation of increased temperatures.

Benmarhnia et al. (2017) reported that in Paris, France green space density (vegetation measured via land cover map) reduced the risk of all-cause mortality in those over the age of 65 during heatwave events (when maximum temperatures exceeded 31 degrees Celsius) between 2004 and 2009.

Pascal et al. (2021) investigated all-cause mortality associated with extreme heat and green space (as measured by percentage surface area green space from land cover maps) in Paris and neighbouring suburbs in France. The authors found that, during extreme heat events, living in areas with less green space was associated with a greater increase in mortality compared with living in areas with more green space. Specifically, the authors found:

- a 94% increase in the relative risk of mortality associated with extreme heat in areas with 37% area surface green space
- a 56% increase in the relative risk of mortality associated with extreme heat in areas with 97% area surface green space.

The authors estimated that up to 884 deaths may have been avoided during extreme heatwaves between 1990 and 2015 if all municipalities in Paris with low surface vegetation coverage had met a minimum threshold of 37% vegetation land coverage.

Goggins et al. (2012) produced a UHI index classification for different areas throughout the city of Hong Kong. The authors reported that a 1-degree Celsius increase above 29 degrees within the city was associated with:

- 0.7% increase in mortality in areas categorised with a low UHI effect
- 4.1% increase in mortality in areas categorised with a high UHI effect.

While the authors did not report if these associations were affected by green space, the cooling effects of vegetation (as measured through NDVI) were taken into account in how the UHI throughout Hong Kong was modelled. This suggests that the observed mortality outcomes are at least partly attributable to the cooling effects of green space on the UHI. Interestingly, the authors also reported on the effects for non-cancer related mortality – a 1-degree increase above 29 degrees Celsius was associated with a 2.3% increase in non-cancer mortality in areas categorised with a low UHI effect, and a 5.2% increase in non-cancer mortality in areas categorised with a high UHI effect.

Another study by Goggins et al. (2013) divided the city of Kaohsiung, Taiwan, into varying districts based on measures of UHI intensity; in so doing, it took into account various urban climate factors, including vegetation (urban parks, forests and agricultural land – based on urban climate modelling), proximity to water bodies, and wind. The authors reported that, in areas with urban climatic conditions and environmental characteristics that exacerbate the UHI effect (that is, 'level 1' districts), a 1-degree rise in mean temperature above 29 degrees Celsius was associated with a 4.2% increase in mortality. This compared with a non-significant increase of 0.3% in areas with less harsh urban and environmental characteristics (that is, 'level 3' districts). Note that, while the authors' methodology accounted for green space, it also took into account a variety of other environmental and urban characteristics; hence, the results cannot be isolated to the effect of green space on temperature reductions *per se*.

Denpetkul and Phosri (2021) examined deaths across 64 provinces and one metropolitan area in Thailand (although the estimate for the latter did not reach statistical significance). They found that up to 2. 5% of deaths were attributable to hot temperatures, and 1.3% to cold temperatures. In relation to green space, every 0.1 unit increase in NDVI was associated with a decrease in rates of all-cause mortality of 0.6% attributable to heat and 0.2% attributable to cold.

Qiu et al. (2021) examined whether green space had an effect on the association between ambient temperature and all-cause mortality in elderly people (aged 65 and over) in China. At a national level, increased green space, as measured by NDVI, decreased the relative risk between heat and mortality. The risk of all-cause mortality associated with the 95th percentile of increased temperatures (44 degrees Celsius and above) was increased by about 32% in areas characterised by the lowest quartiles of green space, and reduced by about 4.2% in areas categorised in the highest quartiles of green space. Interestingly, the opposite effect was observed for cold temperatures. The risk of all-cause mortality associated with the 5th percentile of temperatures (–26 degrees Celsius and below) was lowest in areas characterised by the lowest quartiles of green space (RR 1.52) and highest in areas categorised in the highest quartiles of green space (RR 3.15).

Zhang et al. (2021) examined heat and mortality associations in China, adjusting for a range of demographic variables (such as age and sex) and risk factors (such as smoking and alcohol consumption), as well as other environmental exposures (such as PM2.5 air pollution). The authors reported a hazard ratio associated with each 3-day increase in heatwave days in the year before death of 1.07 for those in the lowest tertile of NDVI, 1.03 in the middle tertile and 1.04 in the upper tertile. In other words, the estimated relationship between heat and death reduced by about 3% with increases in green space, suggesting that green space had a protective effect on mortality associated with heatwaves. Interestingly, these authors also reported the association between every 0.1 unit decrease in NDVI and mortality was about 4% stronger in urban areas than in rural areas.

Sera et al. (2019) estimated that 0.54% of deaths were attributable to heat and 6.05% were attributable to cold when examining for temperature–mortality associations across 340 cities from 22 countries between 1985 and 2014. Among the urban and environmental indicators considered, cities surrounded by rural regions (as opposed to those surrounded by non-rural regions) showed a reduction of 0.19% in the heat-related attributable fraction and an increase of 0.05% in the cold-related attributable fraction (although the latter did not reach statistical significance). The authors reported that green space (vegetation measured via land cover map) mitigated the temperature–mortality effect: higher levels of green space reduced the heat-related attributable fraction by 0.07% and the cold-related attributable fraction by 0.03%, although, once again, the change in the cold-related attributable fraction did not reach statistical significance.

Sinha et al. (2021) used a modelling approach to examine the relationship between air temperature and mortality. These authors simulated various tree coverage scenarios to examine how differences in the amount of trees affected estimates of all-cause mortality due to extreme temperatures. They also considered ozone levels, reasoning that, because ozone is correlated with temperature, not accounting for ozone could lead to overestimating the reduction in mortality that may occur through tree coverage via cooling. After controlling for ozone, they estimated that 247 deaths by extreme heat could be avoided annually by increasing tree coverage (based on land cover maps) in Baltimore by 10% per unit area. By comparison, reducing tree coverage by 10% was estimated to result in 220 more deaths per year, while removing all trees was estimated to incur 551 additional deaths per year.

Son et al. (2016) found that the association between temperature and all-cause mortality (excluding those from external causes, such as from accidents or homicides) was highest for areas with low green space, as measured through NDVI in Seoul, Korea. The authors divided districts of Seoul into 3 groups based on the urban vegetation of each area and estimated the relationship between heat and mortality in each group. They estimated that, for every 1-degree rise in temperature above the 90th percentile (25.1 degrees Celsius), there was an increased risk of mortality of 4.1%, 3.0% and 2.2% for areas categorised as low, medium and high NDVI, respectively.

Kim and Kim (2017) examined the association between mortality rates in people with lower levels of education during heatwaves and multiple measures of green space in Seoul, Korea. Green space measured included green area, green area around buildings and rooftop green area. The latter 2 measures showed effects: based on quantile classifications, the odds of death during heatwaves were estimated to be increased by up to 18% in districts with a low proportion of green space around buildings, and up to 21% in districts with a low proportion of rooftop green space.

Stone et al. (2014) examined heat-related mortality in 3 United States cities (Phoenix, Atlanta and Pennsylvania). The authors reported that, according to their modelling, the greatest concentration of avoided heat-related mortality was seen in the urban core of each metropolitan region, where population densities were highest and the proportion of land surface affected by either surface reflectivity or vegetation (measured via land cover map) was greatest. They estimated that, through various vegetation and surface reflectivity scenarios, increases in heat-related mortality between 2010 and 2050 could be offset by between 40% and 99%.

Choi et al. (2021) examined the association between temperature and all-cause mortality in North Carolina, United States. The relative risk of cold-related mortality was higher in urban areas (RR 1.023) than in rural areas (RR 1.012), as was the relative risk of heat-related mortality (RR 1.006 for urban areas compared with 1.002 for rural areas); however, the difference in heat-related mortality did not reach statistical significance, suggesting it cannot be confirmed that the effect was not due to chance alone. The authors further reported that the association between heat and mortality varied, based on the amount of green space (as measured by NDVI): counties with below-average amounts of green space were estimated to have a higher heat-related mortality risk than those with above-average amounts of green space. A similar effect was found for the effect of green space on cold and mortality; however this appeared to be region-specific, as it was only statistically apparent in the Coastal Plains regions of North Carolina.

Zanobetti et al. (2013) provided a 'case only' approach across 135 United States cities. The authors reported an increase in the relative odds of dying from any medical condition of 3% with a 7.7-degree Celsius increase in warm-month temperature in areas with less green space (below the 25th percentile, measured via land cover map) and of 1% with an 8.6-degree Celsius decrease in cold-month temperature in areas classified below the 25th percentile of green space.

Murage et al. (2020) examined all-cause mortality associated with excessive heat in London, reporting a reduction in the odds of mortality due to heat based on green space exposure (measured via NDVI and tree count). In areas classified as the highest quartile of NDVI, the odds of all-cause mortality associated with excessive heat were decreased by about 1% compared with areas classified as the lowest quartile of NDVI. A similar reduction of about 1% was observed when using the proportion of tree cover, rather than NDVI.

Two studies (Rosenthal et al. 2014; Xu et al. 2013) reported a lack of association between green space and heat-related mortality but significant associations with other exposure measures. Xu et al. (2013) observed a 30% increase in rates of all-cause mortality due to extreme heat in Barcelona, Spain, between 1999 and 2006. No differences in this effect were found based on the percentage of tree coverage; however, an effect for *perceived* greenness was reported. Populations of areas where more than two-thirds (greater than 66%) of residents reported perceiving little surrounding greenness had a significantly higher risk of death than those where less than 14% of residents reported perceiving this.

Rosenthal et al. (2014) found that rates of mortality on extremely hot days (where maximum temperatures exceeded 100 degrees Fahrenheit / 38 degrees Celsius) throughout New York City were increased by about 22% in areas where surface temperatures were above the 75th percentile, compared with areas below the 75th percentile. There was a statistical correlation between mortality and the percentage of impervious surface (the inverse of green space, measured via trees and vegetation via land cover map), and between mortality and remotely sensed surface temperature – but not between mortality and measures of vegetation land coverage. These results do not clarify if green space mitigated mortality through temperature cooling, but they do suggest a mitigating effect of green space, given that rates of mortality increased with both temperature and proportion of impervious surface.

Jang et al. (2020) examined the association between heat-mortality risk and the UHI, as well as several environmental factors in Seoul, Korea. The authors reported that there was no association between indicators of green space and heat-mortality risk, even after adjusting for the UHI effect. However, they did report that indicators of green space (such as urban forestry and green coverage via land cover map and satellite) were *negatively* associated with the UHI effect, and that higher values of the UHI were associated with higher mortality risk in the total population. This effect was not observed for wetlands, the authors' measure of blue space. The authors interpreted this set of findings overall to suggest that, while there was no evidence of a direct association between environmental indicators and heat mortality, there was an effect of the environmental indicators on heat-related mortality risk through an increase in the UHI effect.

Burkart et al. (2016) examined the influence of green space and blue space on all-cause mortality in Lisbon, Portugal from 1998 to 2008 for those aged 65 and over. The authors reported that the association between all-cause mortality and a 1-degree temperature increase above 24.8 degrees Celsius was 15% higher for areas in the lowest NDVI quartile compared with areas in the highest NDVI quartile. A similar effect was also reported based on proximity to water – areas further than 4 km from water showed a 7.1% increase in mortality with a 1-degree increase in temperature compared with an increase of 2.1% in areas less than 4 km from water.

In contrast to this evidence, two of the eligible studies found no effect of green space in relation to all-cause mortality and local climate (Madrigano et al. 2013, Ho and Wong 2019). In their analysis of the relationship between temperature and mortality in Hong Kong, the Ho and Wong (2019) did not find any increase in all-cause mortality risk with a 1-degree Celsius increase in temperature. As there was no association, there was no impact on the effect of percentage vegetation cover (as determined via land cover map). A noteworthy difference in the methodology of this study was that heat effects were analysed across all days with an average daily temperature at or above the 50th percentile, which is not typical for studies in this area. Rather, studies tend to use a much higher percentile threshold, such as the 90th percentile. This difference, the authors reasoned, might explain the null finding.

Madrigano et al. (2013) investigated associations between temperature and all-cause mortality in the United States city of Worcester, in Massachusetts, reporting that extreme heat increased the rate of all-cause mortality by 44% in the 2 days preceding death and 41% in the 4 days preceding death. The authors also reported a marginal increase in the risk of death due to extreme cold temperatures; however, these estimates did not reach statistical significance. Further, there was no significant association between heat-related mortality and green space (measured via NDVI). However, mortality associated with increases in apparent temperature were affected by proximity to blue space – living within 400 m of a large body of water was associated with a reduced rate of mortality, compared with living more than 400 m from a large body of water. However, the findings were not statistically significant.

Two studies reported on mortality outcomes but did not specify the cause of death (Chen et al. 2014; Dang et al. 2018). Both studies reported findings that suggest an effect of green/blue space on temperature-related mortality outcomes.

A modelling study by Chen et al. (2014) considered various urban scenarios throughout the Melbourne central business district (CBD) area (such as replacing 50% of the Melbourne CBD with forest parkland), and the associated consequences for temperature and heat-related mortality. Through these simulations, the authors estimated that increasing the Melbourne CBD vegetation coverage (as determined via land cover map) from 15% to 33% could reduce the average heat-related mortality rate by up to 28%. Estimates of reductions in excess heat-related mortality were up to 99% in a scenario where the entire Melbourne CBD was replaced by forest vegetation.

Dang et al. (2018) estimated the proportion of mortality specifically attributable to the UHI effect in Ho Chi Minh City, Vietnam, between 2010 and 2013. They estimated an attributable fraction of mortality resulting from the UHI of 0.42%, which equated to 30% of the total mortalities resulting from heat in the whole city. The attributable fraction decreased with increasing green space (measured as vegetation land coverage from satellite and urban climate modelling) – an increase in green space of 1 km^2 per 1,000 people was estimated to prevent 7.4 mortalities attributable to urban heat.

A single study was identified that examined the association between infant mortality and measures of green space and temperature. Schinasi et al. (2020) reported that the risk of infant mortality in Philadelphia, United States, increased by up to 22% with every 1-degree increase in minimum daily temperatures over 23.9 degrees Celsius on the day of death. The authors reported a slight indication that the effect may be modified by green space, as there was a higher risk of infant mortality associated with a rise in temperatures in areas with the most tree canopy (measured via land cover map) within a 250 m residential buffer zone, contrary to expectations that greater amounts of tree canopy would result in a decreased risk of mortality. However, the risk of infant mortality did not increase uniformly with increasing amounts of tree canopy, and the observed effect did not reach statistical significance, suggesting it cannot be concluded that it was not due to chance alone.

4.9 Heat-related mortality

Of the eligible articles, 2 reviews and 4 studies examined or mentioned heat-related mortality in relation to green/blue space. Unlike other studies examining mortality, these studies used mortality data where exposure to heat was, to varying degrees, cited as the underlying cause of death.

In their systematic review, Kabisch et al. (2017) cited 5 studies focusing on the role of heat and green space. The authors concluded that, though there is a tendency for a positive association between urban green/blue space and heat-related mortality, the evidence was weak and somewhat inconsistent for the overall relationship.

Heaviside et al. (2017) reviewed several modelling studies that presented data suggesting that increased vegetation can help avoid heat-related deaths. The authors cautioned that it is difficult to validate the estimated impacts of these modelling studies against observed data.

Four studies (described below) were identified that collected data on green/blue space, temperature, and mortality specifically attributed to heat at the time of death. Overall, it cannot be concluded from the results of these studies if there is an effect of green/blue space through local environmental cooling on heat-specific mortality, as each study showed a different outcome:

- Boumans et al. (2014) outlined estimated reductions in non-accidental deaths during heatwaves, based on modelled changes in tree coverage in Travis County, Texas. Estimates ranged from reductions of 1.2% to 2.2% for a doubling of trees, and 2.5% to 3.6% for a 15% increase in tree planting where no trees, at the time, existed. However, the authors cautioned they cannot be confident about these estimates, as they tended to over-predict mortality numbers when compared with historical data.
- Harlan et al. (2013) reported that, after controlling for a number of heat risk vulnerabilities (which included socioeconomic vulnerability and elderly/isolation status) and variation in land surface temperature, a 1-degree Celsius increase in mean land surface temperature in Maricopa County, Arizona, increased the odds of heat-related death by 23%. When controlling for these same vulnerability factors, the proportion of unvegetated area (NDVI) increased the odds by 19%. Note, however, that temperature and vegetation were examined in separate statistical models; therefore, these results cannot determine whether the effect of vegetation had an impact on the effect of temperature. Nonetheless, the authors reported that more statistical evidence favoured

the former model (analysing land surface temperature) than the latter model (analysing unvegetated areas).

- Uejio et al. (2011) examined whether the geographic distribution of heat risk factors – including vegetation health and density (as measured via NDVI), proportion of impervious surface, and night surface temperatures – was related to cases of extreme heat mortality during an extreme heat event in Philadelphia, United States. The authors reported that the geographic distribution of these heat risk factors was not related to heat mortality and that characteristics of neighbourhood stability (such as housing vacancy, house age, and total neighbourhood population) were more influential.
- Gronlund et al. (2015) collected data on heat-related mortality but reported that the percentage of heat-related deaths was too low to use as an outcome.

4.10 Cardiovascular health

One review and 10 studies were identified as relevant for cardiovascular-related health outcomes in relation to the ecosystem service of local climate cooling by green/blue space.

A review and meta-analysis by Gascon et al. (2016) synthesised evidence on the association between exposure to residential green space and mortality in adults. The authors concluded there is moderate evidence for a link between green space and cardiovascular disease mortality. However, only 2 studies were included in their review, which examined for cardiovascular mortality and temperature (heat-related mortality) (Harlan et al. 2013; Uejio et al. 2011). Neither of these studies provided direct evidence of a mediating link or a direct mitigation effect of green space or vegetation.

Overall, evidence among the research-based studies was mixed for the local climate regulation ecosystem service of green/blue space on cardiovascular-related mortality.

A study by Shen and Lung (2016) found a significant effect of green space on rates of cardiovascular mortality in Taipei, Taiwan. The effects were specifically found for green space fragmentation (the degree to which green spaces are separated from one another), patch distance (the distance between green spaces) and largest patch percentage (green space size) (derived from landscape metrics). The authors used a form of structural equation modelling, known as partial least squares. This statistical tool is used to determine causal relationships and to estimate the extent to which observed effects are due directly to the exposure (green space), or mediated by air pollution and/or temperature. The full model – which included effects for both pollution and temperature – indicated that air pollution explained more of the relationship between green space and cardiovascular mortality than temperature. Notably, there was still good statistical evidence for a mediating effect of temperature on the green space/mortality relationship.

Another study by Gronlund et al. (2015) provided evidence of an increase in temperature-related mortality outcomes with a decrease in green space (determined via land cover map). The authors examined death records based on daily temperatures across 8 areas in the state of Michigan, United States. They found that the odds of cardiovascular mortality were increased by up to 14% due to extreme heat. The odds of cardiovascular mortality among those living in areas made up of 91% non-green space were 1.17 times as high during extreme heat as during non-extreme heat. There was no statistical association between cardiovascular mortality and extreme heat in people living in areas made up of 39% non-green space.

More recently, a study by Denpetkul and Phosri (2021) examined the association between daily temperatures and mortality across various provinces in Thailand. These authors estimated that up to 0.7% of cardiovascular mortality was attributable to heat and up to 2.3% was attributable to cold. Furthermore, a positive effect was reported for green space (as measured via NDVI) on this relationship. Every 0.1 unit increase in NDVI was associated with a 0.3% decrease in cardiovascular-related deaths attributable to hot temperatures and a 0.1% decrease in cardiovascular-related deaths attributable to cold temperatures (although the latter estimate did not reach statistical significance).

Madrigano et al. (2013) reported no significant effect for green space (measured by NDVI) on the association between acute myocardial infarction and extreme heat but did report an association based on proximity to blue space. The effect was opposite to what would be expected, based on a protective effect of blue space: the rate of mortality rose by 36% for those living within 400 m of water and fell by 15% for those living further than 400 m from water. Note that this finding was not statistically significant.

In their analysis of the relationship between temperature and mortality in Hong Kong, Ho and Wong (2019) reported that cardiovascular mortality risk was not affected by every 1 unit increase in temperature. Because there was no association between temperature and mortality, there was no effect of green space (determined by the proportion of vegetation cover via land cover map). A noteworthy methodological difference of this study was that the authors analysed heat effects across all days with an average daily temperature at or above the 50th percentile. Typically, other studies use much higher points, such as the 90th percentile or greater.

Studies that have modelled the relationship between air temperature, green space and cardiovascular mortality have reported mixed findings: some provide evidence for an effect of green space on temperature-related mortality and others suggest a negligible impact.

For example, in their modelling study of various tree coverage scenarios in Baltimore, United States, Sinha et al. (2021) estimated that increasing tree coverage (determined via land cover maps) by 10% per area unit could prevent 423 extreme heat-related cardiovascular mortalities in those aged 65 and over. Another 18 deaths by stroke due to extreme heat were also estimated to be avoidable based on the same 10% increased tree coverage scenario.

Conversely, Nyelele et al. (2019) modelled cardiovascular mortality and the ecosystem services of several environmental exposures, including air temperature reductions, based on different scenarios of tree growth in New York, United States. Depending on the rate of tree growth modelled, tree coverage (determined via land cover map) was estimated to increase by between 2% and 5% between 2010 and 2030. However, this was estimated to have a negligible impact on both air temperature and rates of cardiovascular mortality.

Boumans et al. (2014) focused on modelling mortality related to heat stress in Austin, Texas. The results indicated that increased vulnerability to cardiovascular mortality corresponded with areas in which temperatures were increased and vegetation coverage (NDVI) was lacking. However, the authors did not provide quantitative information on the magnitude of this effect.

It is worth noting that several of the included studies analysed whether the odds of dying due to increased temperatures varied, based on pre-existing cardiovascular conditions or risk factors, including:

- hypertension (Rosenthal et al. 2014)
- atrial fibrillation, congestive heart failure and stroke (Zanobetti et al. 2013)
- angina, hypertension, stroke, atrial fibrillation, cardiogenic shock, congestive heart failure, family history of coronary heart disease, and smoking status (Madrigano et al. 2013).

However, these studies did not examine whether any association between these conditions and temperature were affected by green / blue space. Therefore they cannot imply a relationship between cardiovascular health outcomes and the ecosystem service of local climate cooling by green/blue space.

4.11 Combined cardiorespiratory health

Six studies were identified that reported on cardiorespiratory health outcomes alongside measures of green/blue space and temperature. These studies examined either respiratory-related health outcomes or combined cardiovascular and respiratory-related health outcomes. Overall, the results suggest that evidence is limited for an effect of the ecosystem service of local climate cooling on cardiorespiratory-related health outcomes.

Morais et al. (2021) found that the incidence of heat-related mortality (cardiovascular, respiratory) in those aged 65 and over in Lisbon, Portugal, increased by 1.6% with every unit increase in impervious density. Furthermore, the authors found that it decreased by 2.5% with every unit increase in green space (NDVI) and by 4.0% based on the cooling potential of green space (a green space measure that takes into account temperature variations due to vegetation).

In their analysis of daily temperatures in Thailand, Denpetkul and Phosri (2021) examined the association between respiratory-related mortality rates and non-optimal temperatures. They estimated that up to 2.5% of respiratory-related deaths were attributable to heat, and up to 0.5% to cold. The authors also reported that every 0.1 unit increase in NDVI decreased the respiratory-related deaths attributable to hot temperatures by 0.8%, and those to cold temperatures by 0.1%. However, neither estimate for cold-related deaths reached statistical significance, suggesting that there cannot be confidence that this finding did not occur due to chance alone.

Ma et al. (2014) examined the association between temperature and pooled total non-accidental mortality, cardiovascular mortality and respiratory mortality across 17 cities in China. In cities with less than 37.6% green space, the authors estimated a relative risk of heat on daily mortality of 3.87 and a corresponding relative risk of cold of 1.78; in cities with more than 37.6% green space, they estimated a relative risk of heat on daily mortality of 2.00, and a corresponding relative risk of cold of 1.68. However, these differences were not statistically significant, suggesting that there cannot be full confidence that they were not due to chance alone. Note that the authors did not report how green space was measured.

Another ecological study relevant for respiratory-related health outcomes was the analysis of death records in Michigan, United States, by Gronlund et al. (2015). The authors reported no significant association between extreme heat and respiratory mortality, and no effect of non-green space (via land cover map) on this association was observed.

Modelling studies of the relationship between air temperature and cardiorespiratory mortality have reported findings that are similarly limited in their support for a respiratory-related health effect for the ecosystem service of local climate cooling:

- Nyelele et al. (2019) modelled various future tree coverage scenarios in New York, estimating that tree coverage (determined via land cover map) would increase by between 2% and 5% between 2010 and 2030, but that this increase would have a negligible impact on either air temperature or pulmonary-related mortality cases.
- Sinha et al. (2021) modelled various tree coverage scenarios in Baltimore, United States and estimated that increasing tree coverage (determined via land cover map) by 10% would reduce pneumonia-related deaths by 1.

Studies reported by Rosenthal et al. (2014) and Zanobetti et al. (2013) both analysed the odds of dying due to increased temperature, based on pre-existing respiratory conditions (asthma and pneumonia). However, neither examined whether these respiratory conditions were influenced by temperature and green/blue space. Therefore, these results cannot determine the relationship between respiratory health outcomes and the ecosystem service of local climate cooling via green/blue space.

4.12 Diabetes

As only 2 studies examined data relevant to diabetes as a primary health outcome, evidence for a link between diabetes and the ecosystem service of local climate cooling is limited. These 2 studies suggest increases in temperature increase the risk of diabetes-related mortality; however, results are inconclusive as to whether this risk is influenced by green space.

The only study to report a positive effect for green space on diabetes mortality associated with heat was reported by He et al. (2020). The authors reported an increase in the odds of diabetes mortality of up to 20% associated with extreme heat across 60 provinces in Thailand between 2000 and 2008. This effect was mitigated by increased green space (based on NDVI), even after separately controlling for several other factors (including gross domestic product, education, proportion of elderly, and mean temperature). However, when accounting for average humidity, the association between NDVI and heat-mortality was no longer significant. What this indicates is that at least some of the effect of green space on diabetes mortality:

- occurred independently of temperature, given that when the mean temperature was accounted for, the effect remained unaltered
- was accounted for by humidity, because when humidity was included in the model, the effect of green space on the heat-mortality association was no longer statistically significant.

Another study that examined the association between diabetes (hospitalisations and mortality) and temperature in the city of Brisbane, Australia, was reported by Xu et al. (2019a). The authors found increased odds of hospitalisation due to diabetes (OR 1.37) one day after a heatwave temperature spike. A similar increase was observed during the most extreme heatwaves (those defined by the 99th percentile of temperature increases), but this did not reach statistical significance; this suggests that this finding cannot be confirmed to be not due to chance alone. Of note, green space (as measured via NDVI) did not have any effect on the association between heatwaves and hospitalisation due to diabetes, or post-discharge deaths due to diabetes.

Three studies that investigated all-cause mortality or cardiovascular mortality (Rosenthal et al. 2014; Madrigano et al. 2013; Zanobetti et al. 2013) also examined how pre-existing diabetes affected the association between mortality and heat. All showed that diabetes increased the association, but none examined whether this was mitigated by green/blue space. Therefore, the results of these studies are relevant only for knowledge on the association between local climate, diabetes and mortality, and not for the relationship between local climate ecosystem services and diabetes.

4.13 General and mental health

There is limited evidence for an effect of the local climate regulating ecosystem service of green/blue space on general and mental health. While several reviews have noted psychological effects of green/blue space (Jennings and Graither 2015; Kolokotsma et al. 2020), evidence highlighted by these authors was not relevant for the mitigating effect of green/blue space on local climate temperatures.

In their review and meta-analysis on blue space and health, Smith et al. (2021) found that the accumulation of evidence suggested a small but statistically significant effect of blue space on self-reported general health and mental health. Blue space was measured by a range of methods, including land cover maps and geographic information system mapping tools. Measures of general and mental health included self-reported general health via census data and mental-health data captured through instruments such as the 12 Item Short Form, Mental Component Score (known as the SF-12), the World Health Organization's Five Wellbeing Indexes (known as the WHO-5 wellbeing index) and the Warwick-Edinburgh Mental Well Being scale (see Box 5.2 for more detail on these instruments). Overall, the authors reported that, in general, living closer to urban blue space was associated with higher self-reported general health and higher self-reported mental health. However, as with other reviews (Jennings and Graither 2015; Kolokotsma et al. 2020), the report does not outline how blue space confers these health benefits, and therefore cannot elucidate the extent to which these positive health outcomes are derived from cooling of the local environment.

A study by Benita et al. (2019) examined the relationship between public spaces and subjective wellbeing in Singapore. Students wore a sensor that was used to indicate with a button press whenever they felt happy. The sensor also tracked their location and took in air temperature measurements. Results showed that, while no effect for proximity to water was observed, there was a weak significant association between visiting parks (measured via land cover map) and subjective wellbeing. When temperature was included in the authors' model, the strength of this association was reduced. While this might suggest that temperature affects (at least partly) the association between visiting parks and wellbeing, the model simultaneously included several other demographic characteristics and environmental exposures. Therefore, the reduction in the strength of the association between parks and subjective wellbeing cannot be pinpointed specifically to temperature.

A study by Cheng et al. (2021) examined environmental exposures and 'expressed happiness', as measured through sentiments derived from participants' social medial posts. The authors reported increases in expressed happiness with increases in NDVI and proportion of water, and lower expressed happiness with increases in land surface temperature and proportion of impervious land. When all environmental exposures were considered simultaneously, the association between expressed happiness and each environmental exposure remained significant. This suggests that any single environmental factor had a unique effect on expressed happiness, once the other environmental factors had been statistically accounted for. While interesting, this result cannot speak to whether the green space effect occurred through local environmental cooling – although it does suggest that at least some of the effect of any one environmental exposure (for example, green space) on expressed happiness occurred independently of the others (for example, temperature).

Ho and Wong (2019) reported an increase of up to 3.3% in the rate of mortality associated with mental and behavioural disorders with a 1-degree Celsius increase in temperature in Hong Kong. Furthermore, the authors estimated that, after controlling for demographic factors (such as age and gender) and air quality (such as PM2.5 and NO_2), those people with mental and behavioural disorders who died were more likely to have resided in districts with 0.94% lesser green space (measured via vegetation cover on land cover map). It is worth noting that, while the study discussed 'mental and behavioural disorders', the majority (99%) of the deaths analysed in this study were specified as dementia cases. Therefore, these results are more informative for dementia specifically than for mental and behavioural disorders more broadly.

Xu et al. (2019b) examined a number of Alzheimer's-related health outcomes (hospitalisations and post-discharge deaths) in Brisbane, Australia, during summer season middle-intensity heatwaves. Post-discharge deaths due to Alzheimer's showed a relative risk of 1.47 in areas with the lowest proportion of green space (NDVI), compared with a relative risk of 1.0 in areas with the highest proportion of green space. However, this difference did not reach statistical significance and the association varied considerably between health outcomes and according to how the heatwave period was defined. Nevertheless, the broader trend in their findings led the authors to conclude that increasing urban vegetation would likely be effective in easing the negative health effects associated with heat.

4.14 Morbidity indicators

Overall, there is some evidence for an association between green/blue space, temperature, and indicators of morbidity (such as hospital admissions, service access and emergency service use).

In their review, Jennings and Graither (2015) cite evidence from 3 previous studies (Harlan et al. 2006; Knowlton et al. 2011; Solecki et al. 2005) that various socioeconomic factors increase vulnerability to adverse heat-related health outcomes such as hospitalisations for cardiac conditions. While the authors suggest that green space can alleviate these heat-related health effects, it is not clear that the evidence cited links these heat morbidities to the cooling capacity of green space.

A review by Kabisch et al. (2017) suggested that, while there is a tendency for a positive association between urban green/blue space and heat-related morbidities, evidence is weak and somewhat inconsistent. The authors suggest that socioeconomic and environmental factors likely confounded the results, and hence complicated the evidence base; they further highlighted differences in (and limitations of) how green space is measured, as some of the reasons for these inconsistencies.

In their review, Wolf et al. (2020) cited evidence from Kilbourne et al. (1982) and Graham et al. (2016) that there is support for a risk-mitigating effect of trees on heat stroke and heat-related ambulance calls.

Several research-based studies were identified as being relevant for local climate cooling of green/blue space and morbidity indicators:

- Gronlund et al. (2016) reported that the proportion of non-green space did not significantly affect extreme heat and hospitalisation admissions for heat, renal and respiratory diseases in the elderly (65 and over) across 109 United States cities between 1992 and 2006.
- Venter et al. (2020) reported that monthly air temperatures were correlated with the number of skin and subcutaneous diagnoses or hospital admissions in the elderly in Oslo, Norway. The authors estimated that each tree in the city could mitigate heat exposure risk for one elderly citizen by one day.
- Xu et al. (2019a) and Xu et al. (2019b) examined hospitalisations due to diabetes and Alzheimer's (respectively) during heatwaves in Brisbane, Australia. The former study did not find any association between green space (as measured via the NDVI) and diabetes-related hospitalisations during heatwaves, while the latter reported a relative risk of 3.05 for hospitalisations due to Alzheimer's during heatwaves (based on the 95th

percentile of heat with a 2-day lag) in areas with the lowest proportion of NDVI, compared with 1.0 in areas with the highest proportion of NDVI.

- Graham et al. (2016) reported that daily heat-related ambulance calls in Toronto, Canada, were 12% higher during extreme heat events, compared with pre-/post-control time periods. The authors reported that the percentage of canopy cover (determined via land cover map) was negatively correlated with the frequency of heat-related ambulance calls, potentially suggesting that the frequency of these calls decreased with increasing green space.
- Uejio et al. (2011) reported that the rate of heat distress calls in Phoenix, Arizona increased by about 1.0% with an increase in the percentage of impervious surface (the inverse of green space) and by 17% with an increase in maximum night surface temperatures, both of which are indicators of a UHI effect. Unfortunately, the authors did not provide results for the association between rates of heat distress calls and green space, despite having collected data on NDVI.

4.15 Economic impact and health

Avoided costs

Only one study was identified that estimated or evaluated monetary benefits of beneficial health outcomes derived from local climate regulation ecosystem services (Sinha et al. 2021).

Using the Value of Statistical Life methodology, Sinha et al. (2021) reported that estimates of the reduction in baseline annual mortality from increasing tree coverage by 10% (per census block) in Baltimore was valued at US$0.68–2.0 billion (depending on the method used). The authors noted that the estimated monetary benefits from reducing heat were greater than those generated by air filtration services – more than 100 times larger than the value generated from reduced air pollution (PM2.5 concentrations) on average.

Avoided deaths and morbidities

Several studies reported attributable fractions or attributable numbers in relation to avoided temperature-related negative health outcomes based on green/blue space. These studies are included here, given that they could potentially be used for purposes of valuation if their results were to be converted to costs. They include:

- Dang et al. (2018), who reported that the attributable fraction resulting from the UHI in Ho Chi Minh City, Vietnam, was 0.4%. The authors estimated that every 1 km^2 increase in green space per 1,000 people can prevent 7.4 deaths caused by heat
- Sera et al. (2019), who reported an attributable fraction of heat-related deaths of 0.54% across 340 cities over 22 countries. They reported a reduction of 0.19 in the attributable fraction in cities surrounded by a predominantly rural region, and a reduction of 0.07 in the attributable fraction with every square metre of green space per million people
- Sinha et al. (2021), who estimated that the existing tree coverage in Baltimore, United States, reduces extreme heat-related all-cause mortality by 551 deaths per year. These authors estimated a further 247 deaths could be avoided by increasing tree coverage by 10% per unit area, whereas 220 additional deaths would be incurred by decreasing tree coverage by 10%

- Graham et al. (2016), who estimated that increasing the proportional canopy cover in any given census tract from less than 5% to more than 5% could reduce heat-related ambulance calls within the census tract by around 80%
- Venter et al. (2020), who reported that the average tree reduces the potential heat exposure risk for the elderly in Oslo, Norway, by 1.3 ± 0.1 heat risk person days. In other words, every tree removed increases heat risk exposure by about 1 day for 1 person.

4.16 Grey literature

International case study

Kalkstein et al. (2013) modelled various UHI mitigation strategies, such as increasing surface reflectance and increasing vegetation cover, and the consequent effects on heat-related mortality in the district of Columbia (Washington D.C.). The authors reported that an average of 285 deaths between 1948 and 2011 were due to heat-related causes. Using historical weather data, they estimated a potential 7% reduction in heat-related deaths through altering the landscape of the area, and that a further 1% reduction could be achieved through increasing vegetation in the area by 10%, equating to around 20 lives saved per decade. The authors suggested that, while they did not examine hospital admissions from heat-related illness, their results indicate that possibly greater benefits could be expected if more sensitive measures of human health were examined.

Australian case study

Whiteoak and Saiger (2019) modelled various UHI mitigation scenarios (including urban greening and integrated water management – IWM) in an area west of Melbourne. The authors were examining for the associated consequences on morbidity (ambulance attendance and emergency department visits), mortality, and monetary benefits. They examined 3 climate outcomes (cool, average, hot) for 4 scenarios over a 50-year period:

- scenario 1: no IWM regulation
- scenario 2: current IWM policy settings
- scenario 3: potential future IWN policy setting
- scenario 4: targeted UHI mitigation scenario.

The largest benefits from heat mitigation were estimated to have come from avoided deaths and energy savings, with an estimated reduction in avoided deaths of between about A$150,000 for no IWM and urban greening to around A$1.5 million with maximum IWM and urban greening per 100,000 people. In relation to morbidity outcomes for daily maximum temperatures over 30 degrees Celsius, estimated savings ranged from around A$21,500 under the no IWM regulation scenario to A$324,000 for the maximum UHI mitigation scenario for a hot year per 100,000 people.

4.17 Gaps and limitations

Study comparability

Reviews of the health benefits of local climate regulation commonly highlight that study methodologies vary, in some cases considerably, limiting the comparability of studies.

Analytic choices relevant to local climate regulation that have an impact on the comparability of studies include differing approaches to measuring:

- health outcomes: for example, researchers must specify the lag-definition by which to catalogue health data as 'heat-related'. Because the effects of both heat and cold on health might not occur immediately, researchers must incorporate some degree of 'lag' to their choice of what health data should be analysed. In relation to heat, researchers will often use a lag period of 0–2 days, but this varies considerably between studies
- temperature: for example, surface temperature derived from a satellite, air temperature derived from a weather station, or other methods (such as a wrist monitor or meteorological modelling). Further still, researchers must define the choice of temperature threshold (such as the 90th or 95th percentile) by which to categorise data as 'heat-related' or 'not heat-related'
- green space: for example, tree canopy, land use cover maps, or NDVI derived from a satellite. This review identified NDVI as the most commonly used measure of green space (19 out of 40 studies), which itself poses its own limitations (see Box 2.1)
- heat: for example, while several studies categorise heat risk based on percentiles, some use absolute indices (Rosenthal et al. 2014; Venter et al. 2020). Sometimes, these temperature spikes are spatially derived to isolate a 'genuine' UHI effect (Dang et al. 2019), but this is not always the case
- space: for example, some studies examine data at a whole-of-city level, others at the neighbourhood level, and others still at the census tract/group level. This is not a trivial point given the *modifiable area unit problem* – namely, that results are influenced by how data are aggregated. For example, results might provide evidence for an association if data at the level of postcode are aggregated to the census tract level, but not when aggregated to the city level area.

5 Recreation-related ecosystem services

5.1 What are recreation-related ecosystem services?

Recreation-related ecosystem services are ‘the ecosystem contributions, in particular through the biophysical characteristics and qualities of ecosystems, that enable people to use and enjoy the environment through direct, in-situ, physical and experiential interactions with the environment’ (United Nations et al. 2021:133). These services sit within the broader category of cultural ecosystem services, along with visual amenity; education; scientific and research; and spiritual, artistic and symbolic services (United Nations et al. 2021:129).

Cultural ecosystem services provide experiential and non-material benefits to humans; for example, through aesthetic, spiritual, education or recreational experiences (United Nations et al. 2021). Unlike the provisioning and the regulating and maintenance ecosystem services, the benefits of cultural ecosystem services are often considered intangible, subjective or ‘conceptual’ (Milcu et al. 2013; Smith and Ram 2016). For this reason, defining their benefits can be difficult, compounded by the fact that the subsets often overlap – for example, recreational experiences are often intertwined with aesthetic or social experiences (Daniel et al. 2012). As such, the material benefits from these services are traditionally more difficult to quantify than for other ecosystem services (Milcu et al. 2013). Several authors have tried to untangle and clarify these complexities (Fish et al. 2015; Haines-Young and Potschin 2012; Milcu et al. 2013) but some definitional debate still exists.

For the purposes of this review, the definition of the SEEA EA is used; this positions recreation-related ecosystem services as a subset of cultural ecosystem services, and defines them as recreation-related services that benefit both those who live in the vicinity of the services and those who travel to the area to partake of the service (United Nations et al. 2021). This definition separates them from the other cultural ecosystem services, which for the most part are not covered in this review (noting that, as previously stated, these services are often intertwined).

The term ‘recreation-related ecosystem services’ covers a wide range of active or passive activities, including walking, hiking or running, bike or horse-riding, birdwatching and socialising (Vallecillo et al. 2018). Recreation-related ecosystem services are generally considered to occur outdoors (Barton et al. 2019) – in green spaces, such as parks and forests, or in blue space. These environments may be situated in urban or non-urban areas and are generally considered to include publicly available areas (Lachowycz and Jones 2011) such as public parks, although they may also include private land such as backyards (Barton et al. 2019).

How people experience nature is personal and subjective, and can occur through a variety of pathways, including olfactory and auditory stimulation (smells and sounds) and in different temporal (occasional or regular) and spatial (neighbourhood or protected parkland) patterns (Hartig et al. 2014). The postulated benefits of recreation-related ecosystem services are due to experiencing nature in its many forms.

5.2 Overview of the literature

In line with the findings of Hartig et al. (2014) in their review of the relevant literature, the broad range of definitions used to define nature, health and (in particular) recreation-related ecosystem services made it difficult to define and select articles specifically relevant to the topic. To capture the recreation-related ecosystem services component in relation to health outcomes, only articles that discussed nature (in some form, such greenness, green spaces, blue spaces, and so on) with a recreational component were included. This could include measurement of an activity undertaken by participants in areas of greenness (or in relation to green space measurements) or measurement of health in relation to nature spaces that offer a recreational component (rather than the less defined measurement of 'total green space'). This approach provided greater focus on the recreational contribution to health. It also avoided including research where findings on health outcomes related to greenness could not be attributed to the recreational services offered by that greenness, but were instead potentially provided by other ecosystem services, such as air filtration or local climate regulation.

The search strategy for this review identified 28 eligible articles:

- 20 presented original research relating to recreation-related ecosystem services and health
- 6 were reviews of the relevant literature
- 2 were reviews with meta-analyses.

See Appendix B, Table B1 for an overview of the eligible articles.

The following overview organises the findings of recreation-related ecosystem services and health thematically; for example, into categories relating to physical health outcomes and mental health outcomes. However, due to the broad range of definitions of nature and green space, use of green space, risk factors, health conditions evaluated, and methods for evaluating these in relation to recreation-related ecosystem services, there is some overlap between certain of these categories.

Key findings

- In general, recreation-related ecosystem services measured by residing near or spending time in green space were associated with improved health and wellbeing, including improved general mental health.
- Increased physical activity in recreational outdoor areas was associated with better health outcomes in a number of studies.
- Some studies found that physical activity partially contributed to the observed mental health benefits. The remaining benefits for mental health were postulated as being due to 'restorative' elements such as stress relief and mitigation of negative emotions. However, these were not specifically tested for.
- There was evidence that blue space also potentially plays a role in improved mental health, although the mechanisms are not well defined in terms of recreation, and benefits could be due to mechanisms other than recreation-related activities.
- Some studies demonstrated that recreation-related ecosystem services provide measurable economic benefits, through increased physical activity opportunities. Economic benefits are derived from decreased mortality, less living with ill health, and reduced health care costs. There are also potential economic benefits in terms of avoided costs for mental health care , improved productivity and avoided antisocial behaviours. However, accurate measurement of these would require data development.

5.3 Physical health effects

General health

Sugiyama et al. (2008) investigated the association of perceived neighbourhood green space and physical health – as measured by the SF-12 questionnaire (Ware et al. 1996) – of 1,895 adults living in Adelaide, Australia. 'Health' was based on how participants rated their general health, ability to undertake daily tasks, and impact of pain (Ware et al. 1996); resulting scores were categorised as either 'high' or 'low' general health. Level of greenness was also self-reported, and included participants' perceptions of access to parks and bicycle/walking paths, presence of greenery, tree-lined footpaths and 'pleasant natural features' in their area.

The unadjusted analyses showed that those who lived in areas with higher perceived levels of greenness had 40% higher odds of belonging to the 'high' physical health category; this relationship did not alter significantly when adjusting for social and demographic variables (such as age, level of education, income, and work and marital status). However, when the model included recreational walking, the association between greenness and physical health became non-significant, and recreational walking became a significant predictor of physical health. This suggested that walking for recreation may be the mediating factor in the relationship between greenness and better health. However, the authors noted that, as this was a cross-sectional study, causality could not be inferred from these findings.

Zhang et al. (2018) investigated the impact on physical health of green spaces (including those used for physical activity / recreation) to which people were exposed throughout their day, to determine whether causal relationships existed between them (using statistical modelling). Many studies investigating green space rely on measures of vegetation cover in the areas where people reside. However, this study included green spaces that people experienced throughout their day, such as at their place of residence, their workplace/s, and during travel between these, thereby providing greater detail of exposure with time. This Chinese-based study of 1,003 adults included the following measures of 'physical health':

- presence of bodily pain
- impact of physical health on daily activities
- self-rated physical health (collected using the Medical Outcomes Study 36-item Short-Form Health Survey) (McHorney et al. 1993; Zhang et al. 2018).

The authors determined if the observed effect was due directly to the exposure or mediated by another pathway by looking at the direct effects and indirect effects of green space exposure on physical health; they used structural equation modelling, a statistical tool widely used to determine causal relationships.

The results of this analysis, shown in Table 5.1, indicated that physical activity was the driver of the relationship between green space exposure and physical health. That is, physical activity was considered the moderating factor in the positive relationship between green space and physical health, indicating that the positive health benefits seen were derived in total from physical activity.

The authors concluded that the strong relationship between daily green space exposure (not just limited to where people reside) and physical activity indicates that provision of recreational green spaces plays a role in preventing poor health by providing attractive and accessible places to undertake physical activity.

Table 5.1: Effect relationship between green space exposure, physical health, and physical activity, using statistical equation modelling

Total path effect size	Direct path effect size	Indirect path effect size
Green space exposure > physical health	Green space exposure > physical health	Green space exposure > physical activity > physical health
0.018	0.000	0.018

Source: Adapted from Zhang et al. 2018. Results reported as standardised path coefficients.

Life expectancy and mortality

A study by Henke and Petropoulos (2013) investigated ecosystem services with a recreational element in relation to health and social deprivation across Wales. The green space under investigation included areas within Wales that had a recreational focus, such as public forests, nature trails and cycle networks, and included blue spaces (for example, wetlands and marine nature reserves). Socioeconomic factors included income, employment and health-related factors (death rates, life expectancy, health behaviours such as physical activity, and limitations due to long-term illness).

Using regression analyses, the authors found a modest significant correlation between poor availability of recreational areas and death rates but did not find any significant correlations between recreational areas and other measures of ‘health’, such as being overweight or insufficient physical activity. The authors concluded that, while access to recreational land options is likely linked to lower death rates and longer life expectancies, the weak statistical correlation indicates that an array of other factors are likely responsible for human health outcomes, such as genetics or employment conditions.

Vienneau et al. (2017) attempted to determine factors accounting for the relationship between green space and mortality in Switzerland, using population level data of 4.2 million adults, over a mean 7.8-year follow-up period. Using the land use classification data measure of green space (areas of green space that are publicly accessible and can be used for recreation, including rural land and forests with walking tracks), the authors found a protective effect of green space on all-natural-cause mortality (HR 0.94), cardiovascular disease mortality (HR 0.95) and respiratory-related deaths (HR 0.92). Adjusting for the contribution of air pollution (PM10) and transportation noise (decibels) led to around 2–6% and 8% fewer deaths (respectively) from all natural causes; this indicates that the health benefits associated with green space are only marginally attributable to air pollution and traffic noise.

Although the authors did not test for other potential contributing factors (such as specific recreation-related activities associated with the recreational green space), they did propose several mechanisms that may have contributed to the observed decreased mortality:

- physical activity: the greater protective effect of green space on all-cause mortality among the younger population may be because younger people make greater use of green space for physical activity
- recreational use of parks: the greater protective effect of green space for females may be due (so the authors hypothesised) to the fact that mothers with young children may have a higher use of local parks as recreational spaces for their young children (Vienneau et al. 2017).

Note, however, that these conclusions cannot be definitively drawn from this research. Nonetheless, it does contribute to the body of evidence that the association between green space and decreased mortality is not limited to the effects of air pollution and traffic noise, and indicates that the effect of the association with recreational green space should be further investigated.

Blood pressure

Shanahan et al. (2016) examined the impact of nature dose on blood pressure – in terms of frequency of visits and length of time spent in urban green space – in a sample of 1,538 people living in Brisbane, Australia. The authors found in this study that visits by individuals to green spaces for 30 minutes or more a week were associated with significantly fewer cases of high blood pressure. They also determined, via a population attributable fraction analysis, that this would lead to 9% fewer high blood pressure cases if everyone in their sample undertook 30 minutes of nature exposure per week (assuming a causal nature existed). While this study indicates that 'nature exposure' doses of at least 30 minutes a week may lead to a measurable decrease in high blood pressure among the population, the authors did not specifically determine which elements of the nature exposure were associated with the health benefits; therefore, while the study provides good evidence for the impact of nature on health, other causative factors, such as air filtration or local climate regulation cannot be ruled out.

Jimenez et al. (2021) identified 2 meta-analyses in their review that examined the association between green space exposure – in the form of forest bathing and 'nature therapy' (exposure to nature to improve health and wellbeing) – on diastolic and systolic blood pressure. The first of these meta-analyses found decreased diastolic and systolic blood pressure levels in healthy people (as well as in those with hypertension) after exposure to nature, inducing a state of physiological relaxation (Song et al. 2016). The second meta-analysis also found significantly decreased diastolic and systolic blood pressure in those exposed to forest environments, compared with those in urban areas (Ideno et al. 2017).

5.4 Physical activity

Richardson et al. (2013) explored the relationship between the amount of neighbourhood (urban) green space and morbidity, and the mediating role of moderate to vigorous physical activity in health outcomes. In this New Zealand-based study, the authors investigated the role of physical activity, due to its known benefits in reducing the risk of poor general health, overweight and obesity and cardiovascular disease, and in improving mental health. The results showed that people living in the greenest quartile were significantly more likely to meet physical activity guidelines than those living in the area of least green space. Furthermore, those living in greener areas had a significantly lower risk of poor mental health and a reduced risk of cardiovascular disease, after adjusting for sociodemographic variables (for example, age, sex, ethnicity, socioeconomic status and smoking).

However, there was no significant association between amount of green space and general health, nor overweight and obesity. Adding physical activity to the model to determine its mediating effect on the association between green space and mental and cardiovascular health produced only a minor difference to the results, indicating that the positive mental health and cardiovascular outcomes associated with living in more green neighbourhoods is only partly due to the effect of physical activity. This suggests that although physical activity has positive effects on health – and green space is often associated with increased levels of physical activity – physical activity alone was not responsible for the total observed mental and cardiovascular health benefit, and that other elements of green space exposure (unaccounted for in this research) contributed to the improved mental and cardiovascular health.

Vert et al. (2019) sought to quantify the effects of physical activity in a newly regenerated riverside recreational environment in an urban area of Spain on a range of health measures, including:

- all-cause mortality (deaths per year)
- certain morbidities
- DALY.

Conservative estimates (that is, assuming that only 50% of the physical activity being undertaken by the population in the park was new, due to the existence of regenerated park) suggested that this new physical activity would result in 4.8 fewer deaths annually, 4.1 fewer cases of a range of (unspecified) diseases, and 7.4 fewer DALY annually. These values increased on the assumption that 100% of the physical activity undertaken in the park was new and due to the park regeneration – 7.3 fewer deaths, 6.2 fewer cases of (unspecified) diseases, and 11.1 fewer DALY annually. Of the physical activity types measured (walking for leisure, walking for commuting, cycling or running), cycling had the greatest impact, with 5.3 or 7.9 fewer DALY (depending on whether 50% or 100% of the activity was assumed to be new and due to the regeneration) (Vert et al. 2019).

White et al. (2016) estimated the potential health impact of outdoor recreation, calculated as the number of quality adjusted life years (QALY) among 'active' users of outdoor environments in England (see Box 5.1). These environments included urban public open space, allotments, rural parks and pathways, and blue space areas such as beaches and coastlines, but not private residential gardens. Based on previous studies that determined 30 minutes of moderate to vigorous activity per week was associated with 0.010677 QALY per person per year (Beale et al. 2007), the authors calculated that health benefits equivalent to 109,164 QALY per year were achieved through active visits to nature spaces in England. In a further analysis, they estimated a 6% reduction in the risk of mortality, and 542 fewer deaths per year, due to walking-based active visits in outdoor environments. While providing useful estimates of potential health benefits of exercising in green environments, the study had several limitations. The study sample only included those who were physically active on 5 or more days per week – setting a lower threshold for 'sufficiently physically active' may result in a greater number of people being included in the estimates. Also, the study did not include work-related physical activity undertaken outdoors (such as agriculture), and did not include activities undertaken in private gardens, such as gardening, both of which might lead to higher estimated health benefits.

Box 5.1: Quality adjusted life years

QALY measure the number of years of life saved as a result of the intervention, adjusting for the quality of life during those years. One quality adjusted life year is equal to one year of life lived in perfect health.

Shanahan et al. (2016) investigated the dose–response relationship between nature exposure and self-reported physical activity levels among a sample of 1,538 people living in Brisbane, Australia. The authors found that longer visits to green space, and more frequent visits, were associated with higher levels of physical activity, after adjusting for socioeconomic status, age, sex and BMI. However, they acknowledged that the study design did not determine whether the green space exposure causes physical activity, or whether people who are more physically active self-select to live in greener areas.

Two studies investigated the association between green space and maternal outcomes (in terms of birthweight), and the potential role of physical outdoor physical activity in the association (Agay-Shay et al. 2019; Cusack et al. 2018).

Agay-Shay et al. (2019) investigated the association between birthweight and residential proximity to outdoor fitness equipment located in parks. After adjusting for potential confounders (such as socioeconomic status, number of times the woman had given birth, marital status and age), the authors found a small decrease in mean birthweight for those living further from an outdoor park – the mean birthweight decreased by 2.1 g for each 100 m increase in distance to the park. Mediation analysis determined that living further from an outdoor park during pregnancy accounted for up to 14% of the association between green space (measured by NDVI) and birthweight. The authors hypothesised that the outdoor parks may provide beneficial maternal outcomes through opportunities for physical activity, stress relief and social cohesion. However, the study did not account for actual park use, and further research would be required to determine the actual effects of outdoor park use on birth outcomes.

Similarly, Cusack et al. (2018) examined the effect of maternal outdoor physical activity on the association between green space and birth outcomes as a potential explanatory pathway for the effect. The authors found increases in term birthweight with increasing exposure to green space (although these did not reach statistical significance). When testing for the impact of indicators of physical activity on this effect, the association was only slightly attenuated (for maternal neighbourhood walkability), or had no effect (for proximity to parks and water). That is, their results could not determine whether the observed positive association between green space and birthweight outcomes was due to maternal physical activity provided by the physical activity opportunities of the maternal residential green and blue space environment. However, the authors noted that they did not assess actual maternal physical activity levels, and so could not definitively state that the recreation-related ecosystem services that promote physical activity did not contribute to better birth outcomes.

5.5 Obesity

While the search strategy for this review did not return any results relating specifically to overweight and obesity with respect to recreation-related ecosystem services (due to potential limitations of the search strategy), one review by Jimenez et al. (2021) did include evidence of associations between nature exposure and obesity. The authors found that the results were mixed: some studies showed lower levels of obesity in those with greater green space exposure (Bell et al. 2008; Dadvand et al. 2014); others showed either no association (Coombes et al. 2010; Mowafi et al. 2012), a reverse association (that is, higher obesity in areas of higher greenness) (Cummins and Fagg 2012), or associations that differed depending on other factors such as green space type or population density (Dempsey et al. 2018; Liu et al. 2007; Lovasi et al. 2013b). Some of the studies included in this review examined only the association between the presence of green space and obesity (with no measure of recreational element included) (Bell et al. 2008; Dempsey et al. 2018; Liu et al. 2007; Mowafi et al. 2012), although the authors hypothesised that the effects were likely due to increased physical activity. Two studies included measures of physical activity (such as neighbourhood walkability) or access to recreational areas that promote physical activity, in order to explain the findings, but these did not appear to affect the observed associations between green space and obesity (Cummins and Fagg 2012; Lovasi et al. 2013b).

5.6 Mental and psychological health effects

The search strategy returned a number of studies and reviews that mentioned the impact of recreation-related services on 'mental health'. Note, however, that the definitions of mental health varied considerably, as did the methods by which it was measured. See Box 5.2 for an overview of mental health measurement tools included in the search results.

Box 5.2: How was 'mental health' measured?

Mental health can be measured in variety of ways, and validated questionnaires are one useful method for doing this. Many different questionnaires have been developed over time, and the choice of questionnaire used in research depends on the study context and the specific elements within mental health that are being evaluated. The following is a summary of the 7 different questionnaires employed for measuring mental health in relation to recreation-related ecosystem services that were identified among the studies selected for this review:

Questionnaire Name	Abbreviation	Reference	Outcome measure/s	Item examples
Profile of Mood State Questionnaire	POMS	Curran et al. 1995	Emotional state	Tension and anxiety, depression, anger and hostility, vigour, confusion, total mood disturbance
State Trait Anxiety Inventory Questionnaire	STAI	Hidano et al. 2000	Anxiety	Tension, apprehension, worry, nervousness
12 Item Short Form, Mental Component Score	SF-12 (MCS)	Ware et al. 1996	Mental health	Energy, social time, accomplishment, peacefulness, sadness, care
Depression, Anxiety and Stress Scale	DASS	Lovibond and Lovibond 1995	Depression, anxiety and stress	Worry, feelings of panic, nervousness, self-worth
Warwick Edinburgh Mental Well-being Scale	WEMWB	Tennant et al. 2007	Positive mental health	Optimism, usefulness, confidence, energy
World Health Organisation's Five Wellbeing Indexes	WHO-5	Bech et al. 2003	Mental health	Good spirits, calmness, vigour, interest
General Health Questionnaire	GHQ-28	Goldberg and Hillier 1979	Psychological distress	Somatic symptoms, anxiety and insomnia, social dysfunction, severe depression

Note: All tools are validated instruments, and rely on self-report measures.

General mental health

Sugiyama et al. (2008) used the SF-12 (MCS) to investigate the association of perceived neighbourhood green space with mental health. 'Mental health', as measured by the SF-12, was based on participants' responses to a number of questions about the impact of emotional problems on their daily functioning (Ware et al. 1996). Participants were categorised as having either 'high' (better) or 'low' (worse) mental health based on their scores. The authors found that those who lived in areas of greater perceived greenness had almost twice the odds of being in the high mental health category (OR 1.93) as those living in areas of low perceived greenness (OR 1.00) – and this level remained high and significant when adjusting for various socioeconomic and demographic characteristics. When recreational walking was added to the adjustment, the relationship between higher levels of greenness and better mental health scores remained significant (OR 1.44), indicating that recreational walking alone did not fully explain the association between greenness and mental health. This suggests that the benefits of exposure to nature on mental health may be in part related to recreational walking, but that there are likely other factors at play that result in improved mental state.

Rather than measuring the presence or absence of mental illness, Wood et al. (2017) sought to investigate the impact of urban greenness on measures of *positive* mental health, using the WEMWBS (Tennant et al. 2007). Looking at a range of measures and attributes of neighbourhood green space, Wood et al. (2017) found, in their Western Australian-based study, that mental wellbeing was positively associated with the number of parks and the total area of parks within a 1.6 km buffer zone of participants' homes. The number of neighbourhood regional parks (defined as spaces of 20 hectares or more that provide for recreation, sport and conservation and enjoyment of nature) had the greatest effect size on mental wellbeing. However, significant effect sizes were also found for district parks (that is, those 2–20 hectares in size, mainly used for organised sport) and small 'pocket' parks (for local recreation uses, not sport). As well, the authors found that people living in neighbourhoods that met the Western Australian planning policy minimum park provision (defined as '8% of the sub-divisible land area') had better mental wellbeing – on average, scoring 1.6 points higher than those living in areas that did not meet this threshold. Finally, in looking at the function of the green space, the authors found that the 3 park types examined – sporting, recreation and nature – all resulted in positive mental wellbeing scores, although the effect size was greatest for parks providing for organised sport. This study demonstrated that access to local, recreational green spaces of varying sizes and functions resulted in increased positive self-reported mental health.

In their study on green space exposure and health, Zhang et al. (2018) also used the concept of mental wellbeing rather than illness, using the WHO-5 (Bech et al. 2003). Using statistical equation modelling to investigate the relationships, the study found that there was a direct positive effect between daily green space exposure and mental wellbeing, and that the magnitude of this was greater for those who were exposed to more green space throughout their day (including in their residential area, work area and while travelling). In adding physical activity to the model, as a potential mediator of the causal pathway between green space and mental wellbeing, the authors found that physical activity explained some of the positive impact on health. The impact of green space exposure on mental health had a direct effect size of 0.228, while the indirect effect size (physical activity as a mediator) was much lower (0.018) (Table 5.2).

Table 5.2: Effect relationship between green space exposure, mental health, and physical activity, using statistical equation modelling

Total path effect size	Direct path effect size	Indirect path effect size
Green space exposure > mental health	Green space exposure > mental health	Green space exposure > physical activity > mental health
0.228	0.21	0.018

Source: Adapted from Zhang et al. 2018. Results reported as standardised path coefficients.

These findings indicate that elements of daily green space exposure, other than physical activity, provide positive mental wellbeing outcomes; while the authors did not examine what these factors were, they postulated that stress relief, relaxation and mitigation of negative emotions may be possible pathways to better mental wellbeing.

Depression

Shanahan et al. (2016) investigated the impact of nature exposure doses on depression in Brisbane, Australia. Depression was subjectively measured using the DASS scale (Lovibond and Lovibond 1995). The authors found that the odds of having depression were significantly lower for those who spent at least 30 minutes a week in an urban nature environment, and that there was an incremental decrease in the odds of depression with increased time spent in this environment – plateauing at 1 hour and 15 minutes (Shanahan et al. 2016). This indicated that more time spent in nature was associated with improved mental health. After performing a population attributable fraction analysis, the authors found that up to 7% of cases of depression could be avoided if the sampled population experienced at least 30 minutes of nature exposure a week.

Again, it should be noted that this study did not determine which elements of nature exposure were responsible for the associated health improvements; therefore, these results can only contribute to the knowledge base of nature exposure and health in a general manner.

In their longitudinal study of pregnant women in the city of Bradford, England, McEachan et al. (2016) examined the relationship between residential green space and depression in pregnant women, as measured by a modified version of the GHQ-28 (Goldberg and Hillier 1979; Prady et al. 2013). They found that those living in areas with higher amounts of green space within a 100 m buffer zone (measured by NDVI) were associated with lower odds of reporting depressive symptoms (between 18% and 23% lower) than those living in areas with lower amounts of green space.

The authors then sought to determine whether physical activity moderated or mediated the relationship between green space and depression – that is, did the strength of the association vary depending on participants' physical activity behaviours (moderation) or did physical activity explain part of the reason for the association (mediation)? In the unadjusted models, the authors found that those with higher amounts of green space within a 300 m buffer zone of their residence were significantly less likely to report depressive symptoms during pregnancy. However, after adjusting for ethnicity, demographics, socioeconomic status and health behaviours (such as smoking and alcohol intake), the relationship remained significant only for those who were physically active. This indicated that the protective effect of greater amounts of green space on depression during pregnancy was strongest for those who are physically active.

Further, the authors determined that physical activity mediated, or accounted for, 7.8% of the relationship for those in the 100 m residential buffer zone, decreasing to 5.6% within the 500 m buffer zone. Therefore, the benefits of green space on pregnancy depressive symptoms were only partly due to the physical activity opportunities they provide, and other mechanisms (such as air filtration or local climate regulation) should be investigated in a similar way to determine their contribution to the association.

5.7 Other potential health benefits

The studies mentioned earlier provide examples of how health benefits can be measured in relation to recreation-related ecosystem services at a large, population scale. The search strategy also revealed some interesting literature on the benefits of green spaces to health through recreational opportunities, although the experimental methods used to determine these benefits limited the extent to which the findings could be generalised to the wider population. More work would be required to determine the extent of their impact on a larger scale.

Limitations included very small sample sizes (between 13 and 77 participants), single sex studies and the young age of participants, or the use of experimental methods that are not practical to conduct at the population level. While they cannot be applied to the population as a whole, these findings have been included here for discussion, as part of the extensive review into potential health benefits of green and blue space. They do offer useful insights into some health effects that are currently unaccounted for in other larger studies.

Findings included:

- anxiety – significantly lower self-assessed anxiety (as measured by the STAI questionnaire) in those who spent 15 minutes walking in urban forests during winter (that is, during leaf-off season) (Song et al. 2013), and in rural forests (Joung et al. 2020), compared with those who spent 15 minutes walking in urban areas. The study sample sizes were 13 and 24 participants, respectively
- mood – significantly improved self-assessed mood (as measured by the POMS questionnaire) for those who spent 15 minutes walking in urban forests during winter (that is, during leaf-off season) (Song et al. 2013), and in rural forests (Joung et al. 2020), compared with those who spent 15 minutes walking in urban areas (study sample sizes of 13 and 24 participants, respectively). Significantly improved mood (as measured by the POMS questionnaire) among those who spent 15 minutes walking in, or simply sitting in and viewing a forest environment compared with those undertaking the same activities in urban environments (study sample size of 57 participants) (Kobayashi et al. 2021)
- relaxation – induced relaxation (as measured by heart rate variability) in those taking a small amount of gentle exercise in forested areas (Joung et al. 2020; Song et al. 2013) compared with those undertaking the same activity in urban areas (study sample sizes of 13 and 24 participants, respectively)
- stress – lower stress levels (as measured by salivary cortisol) among those undertaking a 15-minute walk in a rural forest compared with those undertaking the same activity in an urban area (study sample size of 24 participants) (Joung et al. 2020). However, the findings of this study contrasted with those of 2 studies included in a review by Grilli and Sachelli (2020), which found that forest exposure appeared to have an insignificant or no effect on lowering cortisol levels. The effect was potentially due to the short duration of the stimulus, which was insufficient to activate a cortisol response (Beil and Hanes 2013; Tyrväinen et al. 2014), and because the included studies had small participant numbers.

The literature search also returned one extensive review by Andersen et al. (2021) on the impact of nature exposure on immune system functioning. Many plants, and in particular conifers, are known to emit BVOCs (which can provide plants with antimicrobial protection) and terpenes (which produce the characteristic odour of plants) (Cho et al. 2017; Kuo et al. 2015; Laothawornkitkul et al. 2009). As these compounds are present as aerosols in forest areas, it has been hypothesised that inhaling them is at least partially responsible for positive health effects found in studies on 'forest bathing' – or *Shinrin-yoku*, an immersive recreational activity, often undertaken in Japan and Korea, that has been found to have positive health effects (Cho et al. 2017; Song et al. 2016; Tsunetsugu et al. 2010).

In their review of the subject, Andersen et al. (2021) found that forest bathing studies resulted in increased markers of immunity (such as natural killer cell levels), specifically as a result of inhaling BVOCs while in these environments. The meta-analysis also found that exposure to waterfalls led to anti-inflammatory responses and decreased allergic responses. These results provide support for the immunological benefits provided by exposure to natural environments through recreational pursuits such as forest bathing. The authors noted, however, that determining whether these immunological responses translate to prevention of immunological diseases requires further investigation. Currently, while recreation-related ecosystem services appear to play a role in stimulating potentially powerful immunological responses, there is a lack of evidence to link this response to quantifiable health outcomes at the population level.

Two papers on biodiversity in relation to recreation-related ecosystem services and health were identified. One was a small study (n=22) on perceptions of biodiversity in alpine regions, and impacts on psychological health (Hussain et al. 2019). This study did not find any significant changes to heart rate measurements between the more and less biodiverse environments, but there were higher levels of self-reported health benefits between the two. The second paper, a review by Sandifer et al. (2015) mentioned a range of health benefits in relation to more biodiverse nature exposure (without specifically examining recreation-related ecosystem services). However, the authors also acknowledged data deficiencies in determining the health impacts of the cultural ecosystem services, in particular. This highlights the need for better data development to determine health impacts of increased biodiversity in recreation-related ecosystem services.

5.8 Blue spaces and health

Most of the literature discussing health effects of nature referred to the impacts of green space on health. However, green space is rarely uniform, and may include natural or artificially constructed bodies of surface water, such as ponds, fountains, lakes, rivers, canals and so on – that is, blue spaces. The impact of these blue spaces as part of the natural environment are often not accounted for (Smith et al. 2021).

However, the search strategy returned 2 review articles that focused solely on the contribution to mental health of recreation-related ecosystem services provided by blue spaces (Gascon et al. 2017; Georgiou et al. 2021). A third review focused on the contribution of blue spaces to a range of physical and mental health outcomes (Smith et al. 2021).

A systematic review by Gascon et al. (2017) identified several studies relating the impact of blue spaces such as lakes, rivers and seas (independently from green spaces) on mental health and wellbeing. Conditions that the authors considered to be part of 'mental health' were varied and included behavioural and emotional problems, wellbeing, self-esteem, mood, stress, psychological distress, life satisfaction, happiness, mental restoration, depression and anxiety. Tools to measure these conditions also varied widely: some studies used validated questionnaires, such as the GHQ-28 (Goldberg 1972), while others used either existing health surveys, or information on the use of mental health services (such practitioner visits or mental health prescribing) (Gascon et al. 2017). The authors found mixed evidence of the contribution of blue space to mental health. Some studies did not find an association between the size of, or access to, blue spaces and the mental health condition or service use being investigated; others revealed improvements in terms of better mental health, fewer emotional problems in children, and increased happiness. However, these studies solely investigated the proximity, access to and time spent in various types of blue space, not whether the blue spaces were used for recreation. Therefore, the benefits cannot definitively be ascribed to the recreation-related ecosystem service, as they may arise from other services, such as air filtration or local climate regulation.

A second review of the impacts of blue spaces on health by Georgiou et al. (2021) examined the element of 'restoration' (that is, relief from the stresses of daily life, to return to a more balanced physiological and mental state) in relation to blue space. Again, a variety of measures were used that fall under the umbrella of 'restoration', such as attention restoration, self-reported history of depression, self-reported negative feelings, life satisfaction and others. The authors found that, in general, living closer to blue spaces, or in areas with greater amounts of blue space, resulted in positive impacts on restoration in adults, although one study of children did not find an association. A meta-analysis of these studies showed that being in contact with more blue space was associated with more restoration, although there was no indication whether being in contact with blue space translated to recreational use.

Smith et al. (2021) conducted a systematic literature review and meta-analysis of the contribution of blue space to physical and mental health and wellbeing. The meta-analysis determined that blue space had significant, if small, positive effects on physical health in terms of all-cause mortality, self-reported general health, and obesity. Of the wide array of mental health measures included in the meta-analysis, only self-reported 'mental health and wellbeing' was significantly positively affected by exposure to blue space. The authors stated that while the calculated effect sizes of positive impact were small, heterogeneity in research methods included in the meta-analysis likely underestimated the actual contribution of blue spaces to health. Furthermore, the effect sizes of health benefits from blue space were similar to those provided by green space.

While the review and meta-analysis by Smith et al. (2021) provide an accumulation of evidence for the positive health benefits of exposure to blue space (independent of green space), as with reviews by Gascon et al. (2017) and Georgiou et al. (2021), the study did not examine whether the blue space provided better health through increased recreational opportunities, or whether the health benefits were a result of other factors, such as other cultural ecosystem services, air filtration or local climate regulation.

5.9 Recreation-related ecosystem services, health and the COVID-19 pandemic

During the height of the COVID-19 pandemic, many countries introduced public health measures to contain the spread of the virus. While the type and extent of restriction varied among countries, for many it entailed social distancing, working from home, limiting the amount of time spent outdoors, and travel restrictions. Based on the biophilia hypothesis – that is, that humans are, by nature, attracted to spending time in nature (Kellert and Wilson 1993) – changes in daily patterns might be expected to have an impact on the way people use nature, and the benefits they derive from it. Research on the impacts of COVID-19 restrictions on human interaction with the environment and the effect on health is starting to emerge.

One United Kingdom-based study by O'Brien and Forster (2021) sampled 2,115 people with an interest in nature, trees and woodlands, to examine changes in their physical activity and wellbeing – as well as their level of engagement with nature – during the pandemic-related restrictions in England in June–July 2020. The study found that:

- 59% of respondents who had been physically active in the previous week of lockdown had done a bit more, or much more physical activity than normal
- 69% of respondents claimed they would maintain their increased outdoor physical activity levels in the long term

- respondents who were less active were significantly more likely to have fewer visits to nature – between 16% and 24% fewer (depending on the nature type; for example, urban green space, countryside) than those who were more active.

Furthermore, more than two-thirds of respondents reported an increase in feelings of connection to nature (such as ‘time taken to appreciate nature’ and ‘level of happiness when in nature’) as well as an increased appreciation of trees in different environments (such as woodlands) in the streets and along waterways. Those who were more physically active reported that they were more likely to visit nature areas for physical activity and for other reasons – such as connecting with nature, learning, and challenging themselves.

Although this study was non-representative and based on subjective measures of physical activity, wellbeing and engagement with nature, it provides evidence that during a time generally seen to be unusual and stressful, nature and green space provide opportunities to increase physical activity, personal wellbeing and feelings of connection to nature.

Another study, of 730 residents based in a city in Finland, also found self-reported increased levels of outdoor recreation in almost half of respondents, and increased visits to forests, semi-natural and neighbourhood recreational sites compared with pre-pandemic levels (Fagerholm et al. 2021). As well, the impact of nature on subjective wellbeing was generally positive, with responses to a range of subjective wellbeing questions ranging from 49% to 97% of people agreeing strongly or partly with statements such as ‘natural environment has been an important supporting factor for my wellbeing during COVID-19’ and ‘spending time in nature instead of the built environment is important for my positive mood’.

Both these studies are subjective, non-representative and not quantifiable in a way that allows conclusions to be drawn about financial benefits gained from nature due to physical activity and/or wellbeing. However, they do highlight a change in appreciation for and use of natural spaces, and the potential for these to positively protect health (via improved mental and physical wellbeing) during wide-scale crises, thus likely increasing their societal value. More research is likely to become available soon on the impacts of COVID-19 public health restrictions in relation to recreation-related ecosystem services and health.

5.10 Economic impact and health

The search strategy revealed 6 studies that discussed the economic impact of nature exposure on health (Buckley and Brough 2017; Mekala et al. 2015; Moseley et al. 2018; Shanahan et al. 2016; Vert et al. 2018; White et al. 2016), with considerable heterogeneity in the methods of evaluating the values.

Vert et al. (2019) performed a health economic assessment of the impact of physical activity in a newly regenerated riverside park development on all-cause mortality (using the Value of Statistical Life method) and on direct health costs of disease. In their analysis, the authors included 2 scenarios: firstly, the assumption that only 50% of the physical activity undertaken in the park was due to the new park regeneration and, secondly, the assumption that 100% of the physical activity was due to the regeneration.

Using reduced mortality calculated from these scenarios, the authors estimated annual reductions of between €15,524,195 and €23,403,186 in one year. Additionally, they estimated reduced annual health care costs of between €19,849 and €29,943. These estimates were based on the park use profiles of the survey participants, the estimated daily numbers of park users, epidemiological studies (to determine physical activity – health outcome estimates) and administrative health data (physical activity levels, mortality and disease incidence rates among the local population). The authors noted that these calculated benefits could be greater if extended to populations outside those included in the survey.

Thus, the blue-green space provided by the regeneration of an urban riverside area provided physical activity opportunities resulting in considerable health advantages with economic benefits.

Moseley et al. (2018) quantified the economic cost of a range of physical activities undertaken in 14 non-urban woodland environments in England and Wales. By categorising activity types undertaken (such as walking, leisure cycling, horse riding, mountain biking and running) into intensity levels, and assessing the length and frequency of park visits, they were able to determine the amount of energy spent due to physical activity in the parks (as measured by Metabolic Equivalence of Task, or MET, units), calculate QALY and produce an economic assessment of the benefits of physical activity in the woodlands.

The types and intensities of recreational experiences varied depending on the woodland type: some areas were used more frequently for higher intensity activities, while others had a greater proportion of lower intensity physical activity visits. Accordingly, the total QALY generated by woodland use varied, from a low of 0.129 to a high of 3.542. The authors assigned the economic cost of 1 QALY, valued at £20,000, which was based on previous analyses relating to the National Health System in the United Kingdom (NICE 2013). The resulting QALY monetary estimates derived from a visit where a specific physical activity lasting 30 minutes or more occurred ranged from £6 to £8,542 per person, across the sites, with totals of all respondents surveyed at each site amounting to between £2,581 and £70,832 per site. This study demonstrated the utility of a physical activity indicator to determine an economic value of health benefits generated from physical activity use of recreational woodland areas in England and Wales. It is conceivable that a similar method could be applied to other areas.

A second United Kingdom-based study used the above-mentioned NICE value of a QALY to economically evaluate benefits of nature-based physical activity. In their study of recreational physical activity in natural environments in England, White et al. (2016) estimated the economic value of exercise in nature undertaken by physically active people. Having calculated a health benefit of 109,164 QALY per year due to this activity, and applying the NICE recommendations of 1 QALY being equivalent to £20,000, the estimated annual welfare gain was calculated to be around £2.18 billion. A further analysis (estimating avoided mortality based on active participants walking in these same outdoor environments) to test the robustness of their results determined a 6% reduction in the risk mortality, and 542 fewer annual deaths due to active participants walking in these environments. The associated monetary benefit from this activity was estimated to be around £1.75 billion per year. This study was based on participants who met the physical activity guidelines and did not include activity undertaken in private green space (such as gardening). Therefore, it is likely an underestimate of potential monetary benefits due to recreational physical activity undertaken in outdoor settings.

Mekala et al. (2015) developed a business case to value the benefits of a proposed creek rehabilitation project in a lower socioeconomic area of Melbourne. The authors estimated the economic benefit of increased physical activity that the development would potentially generate among the local population in terms of avoided health care costs of insufficient physical activity. Using a pre-determined assumption that the annual cost of insufficient physical activity is A$756.66 per capita (from Dedman 2011), the study determined the dollar value of avoided health care costs, using publicly available demographic data on the current level of insufficient physical activity in the catchment area. It then applied this dollar value to each of 3 scenarios of increased physical activity due to the park regeneration – a 10%, 12% or 15% increase in physical activity. This equated to annual savings of A$75,049, $90,059 and A$112,574, respectively.

Calculation of avoided health care costs by this method lacks detail – for example, about the type of activity undertaken, the frequency of visits, energy expenditure and so on – and can only be used as a guide for the economic impact generated by a recreation-related ecosystem service on health. However, the business case does demonstrate how indicative values can be easily calculated to investigate potential health care related values of recreation-related ecosystem services.

Shanahan et al. (2016) did not perform a detailed economic evaluation of recreation-related ecosystem services and health. However, their study of the impact of nature doses on self-reported mental health (depression) and high blood pressure (as determined by self-report of taking blood pressure medications) determined that 30 minutes of nature exposure would result in up to 7.0% fewer cases of depression and 9.0% fewer cases of high blood pressure. Extrapolating from these findings, the authors suggested that this could translate into substantial cost savings, based on estimates of AU$12.6 billion per annum in societal costs of depression in Australia. However, this is an indication of costs savings only, and not based on the type of detailed analysis that would be in line with SEEA EA accounting principles.

Based on the concept that economic valuation of conservation land use should include the cost of human health, Buckley and Brough (2017) investigated the psychological health improvements from direct use of park ecosystems (mental health improvements in visitors) and proposed a framework to quantify this. The framework involves 3 main steps:

1. defining people and their nature experiences (for example, age, length of exposure)
2. quantifying the psychological health outcomes from the experience
3. calculating the economic outcomes and values of the health impact.

The economic values are derived from avoided mental health care treatment costs, improved work productivity and avoided antisocial behaviours (such as vandalism or domestic violence). Noting that currently the data to support these costs have not yet been extensively developed, a broad estimation can be calculated; for example, by including estimates such as:

- the proportion of the 24 million people in Australia visiting urban green space (90%) or national parks (around 75%) annually
- the proportion of Australians experiencing mental health issues annually (greater than 20%)
- the proportion of Australians using mental health services annually (about 8%)
- the current estimated cost of mental illness in Australia (A$200 billion).

The authors noted that the model would need information on the mental health of park users, and on the health outcomes for the various types of visits to parks and patterns of use, longitudinally (short-term and longer term exposures), before it could be applied; however, it provides a useful framework for the inclusion of health in valuing park ecosystems services.

5.11 Grey literature

International case study

Paths for All – a partnership project developed between Glasgow Life and NHS Greater Glasgow and Clyde, and carried out by greenspace scotland (Paths for All 2013) – was developed to promote walking opportunities across Glasgow among population groups least likely to undertake regular exercise. Using a Social Return on Investment analysis to calculate the social, environmental and economic impact of the program, the result included a cost–benefit ratio to help evaluate its effectiveness. For example, a ratio of 1:3 indicates that an investment of £1 in the activities has delivered £3 of social value. The analysis was undertaken at an individual rather than a population level, with some economic outcomes as follows:

- NHS Greater Glasgow and Clyde: applied costs savings to the National Health Service (NHS) in relation to reduced prescription costs. This was achieved through questioning participants on their medical conditions and identifying individuals who were able to reduce their blood pressure from regular physical activity and thus require less drug therapy
- Glasgow City Council: reported a reduced demand for home care as walkers reported better mobility and fewer falls due to increased agility and movement.

However, these findings likely underestimate the benefits provided through the walking program as the study noted the challenge of capturing the multiple health benefits of regular walking within the time frame. This led to the commission of a longitudinal study to follow a cohort of walkers over 3 years. The study acknowledges that a preferred approach would have been to use QALY to measure both the quality and quantity of life. Instead, it used the Health Economic Assessment Tool to estimate the value of reduced mortality that results from specific amounts of walking. Calculations using this tool estimated that participation in health walks would result in 0.04 avoided deaths per year, leading to a current value of the annual benefit of £2,580, averaged across 1 year. Furthermore, based on evidence that physical activity can help prevent falls, the report estimated that preventing falls in just 10% of participants who reported improved mobility as a result of taking part in the walks would equate to a saving of £11,0934 (based on the economic cost of hip fractures in the United Kingdom).

5.12 Gaps and limitations

Recreation-related ecosystem services terminology

One of the challenges in performing the literature search for recreational-ecosystem services was the lack of consensus in terminology used to describe recreation-related ecosystem services. Many different activities potentially fall under the category of ‘recreation’, although they may not have the specific label of ‘recreation’. For example, while physical activity is often readily identified in the literature as recreational, it is perhaps less obvious whether ‘nature therapy’ would be considered a recreational pursuit (rather than a therapeutic intervention). Indeed, physical activity, in itself, may not be recreational, but functional, such as walking or cycling for transport. Additionally, the health impacts related to recreation are broad, often subjective, and often focus on ‘wellness’ elements rather than defined illnesses. The locations in which recreational activities take place may be broad (for example, ‘in nature’) or specific (for example, in urban parks with cycle tracks). Indeed, some studies included measurements of self-reported physical activity levels that did not differentiate between physical activity undertaken in nature and indoors, or indicate whether the physical activity was recreational or incidental exercise – thereby limiting the ability to assign observed results to the effects offered by recreation-related ecosystem services.

Due to the variation in definitions, it was decided to conduct a broad assessment of the literature, with the inclusion of relevant health impacts related to the search. This approach returned 28 papers relevant to recreation-related ecosystem services and health. However, it is possible that including different search terms would have revealed other papers that may have fallen into the category of recreation-related ecosystem services and health impacts.

Social health

Some of the studies included concepts of 'social health' as a measure of health. This was considered to be beyond the scope of this review, as social health encompasses elements that more closely align with welfare (such as social engagement). However, in line with the WHO definition of health as 'a state of complete physical, mental and social wellbeing' (WHO 1946), including these measures would possibly increase the value of recreation-related ecosystem services.

Diabetes

Despite the observed association between greater green space exposure and lower rates of type 2 diabetes and obesity, the literature search revealed only one review – that found mixed results for the association between obesity and recreation-related nature exposure. No papers were found relating to type 2 diabetes. Including diabetes-related terminology in the search term may have returned more results, and this remains an area for possible further targeted investigation.

6 Discussion

For all 3 ecosystem services, there was evidence to support the contribution of the services to health, and in some cases, for the associated economic benefits, in both the formal academic literature and in non-peer reviewed grey literature.

Air filtration had the most evidence. The benefits were determined in the context of removal of air pollution (variously measured in terms of particulate matter, nitrogen dioxide, ozone, sulphur dioxide, or a combination of these) and by a range of vegetation types, such as forests, urban green space, grasslands, shrubs and agricultural land. Only one study reported on economic benefits in Australia (in the Australian Capital Territory); the remainder of the evidence related to international studies (at the national, regional or city level). Greater economic benefits were seen in more vegetated areas with higher population density. This was explained by the greater capacity for air filtration in areas with more vegetation coverage, and the greater potential for health benefits in more densely populated areas.

The evidence for economic benefits to health from recreation-related ecosystem services was mostly derived from increased physical activity opportunities in green space or nature. Non-physical activity-related economic impacts of recreation-related ecosystem services included avoided treatment costs for mental health / depression and avoided high blood pressure. Recreation-related ecosystem services are not restricted to people's residential or local environments and, accordingly, several of these studies examined the economic benefits in relation to tourism (for example, visits to national parks). Others centred on local initiatives, such as neighbourhood park developments.

The review of the literature for local climate regulation revealed fewer examples that investigated economic impacts – one peer reviewed article and 2 non-peer reviewed case studies. However, despite the lack of studies specifically focused on economic benefits, several studies reported data that could potentially be used to develop valuation data. For example:

- avoided heat-caused deaths per increase in measure of green space
- heat-related deaths attributable fraction per area of green space
- avoided all-cause mortality per percentage increase in tree canopy
- reduction in ambulance call-outs proportional to tree canopy cover.

For all 3 ecosystem services, there is little evidence of studies employing the SEEA framework to determine economic health benefits. Only 2 papers (in relation to air filtration) specifically sought to assign health-related costs using SEEA EA principles. Nonetheless, the review revealed a range of ecosystem service-related health impacts that can be used in developing economic measures in terms of health benefits.

The literature provides a detailed and nuanced picture of the evidence base from a broad range of geographic regions. While there were fewer Australian-specific studies, the evidence from Australia was broadly consistent with that from international studies. However, regional differences in populations, climates, economies and health systems exist between countries and at more local, county, state and city levels. These variations are important considerations in program and policy development.

Many of the data sources used to determine the health and economic benefits supplied by the ecosystem services are readily accessible, or currently being developed in the Australian context. The Australian Burden of Disease Study reports on a range of health measures that demonstrate the health and economic impact of various risk factors (including air pollution and physical inactivity) and diseases (AIHW 2021b). Satellite data exist for measuring air pollution and vegetation coverage – and the software i-Tree eco, which quantifies air pollution removal by trees and the associated human health benefits, has been adapted to the Australian context.

Data development is required to inform further about health benefits. For example, recreation-related health benefits of national parks would require estimates of the number of users and amount of time undertaken for different types of activities, such as walking and bike riding.

6.1 Limitations and considerations

A number of factors potentially limit the interpretation of the findings of this review.

Firstly, there are several methodological considerations. To establish an effect of any ecosystem service on human health, data from at least 3 measures need be included in a study:

1. an environmental exposure, such as exposure to vegetation or proximity to water
2. an environmental exposure related to the ecosystem service, such as air pollutants
3. a human health outcome, such as disease or hospitalisation rates.

The quality of evidence is affected by how these measures were defined, as well as by the way in which data were analysed. An important component for determining the relationship among these 3 measures is temporality – that is, the order in which the exposure and the outcome occurred. At the population level, cohort studies are useful, as they can determine whether the outcome occurred before or after an event. However, many of the research articles included in this review were cross-sectional in nature – that is, they looked at the exposure and outcome at a single point in time. This does not allow for conclusions to be drawn about the order in which events occur, and thereby diminishes confidence in the strength of the association between the 2 factors.

A number of the included studies used mediation analysis to examine the impact of mediating factors on the relationship between an exposure variable and an outcome variable – for example, to determine whether the positive association observed between green space and lower rates of cardiovascular disease was due to physical activity and, if so, how much of the association was due to this. This statistical technique has the potential to provide additional support for linking the benefit of the ecosystem service to the health outcome (in this example, green space provides the opportunity for increased physical activity, which can lead to better cardiovascular outcomes). However, mediation analysis is not without its limitations. For example, this method makes assumptions about temporality (that is, that the exposure precedes the mediator and the outcome) (Rijnhart et al. 2021). It is therefore best used in longitudinal studies to determine that the order is correct. A more robust method to determine causality is to use the more recent statistical method of causal mediation analysis, which overcomes some of the methodological weakness of traditional mediation analysis. However, this review did not uncover many studies using this method.

There was also considerable variation in how exposures and outcomes were measured. For example:

- air pollution – a wide range of pollutant types and numbers of pollutants included in the studies (NO_2, O_3, PM10, PM2.5, SO_2) were assessed individually, or together, or in some combination

- heat measurements – variations included ground-based versus satellite measurements, percentile cut-off points for identifying extreme heat (50th, 90th or 95th percentile), identification of heatwave lag period for capturing heat-related morbidity and mortality
- green space – variations in how green space was measured (NDVI, tree canopy or count, land cover maps, self-reported level of green space)
- physical activity – variously assessed as MET units, self-reported physical activity levels, or proximity to outdoor exercise areas
- mental health – a wide range of mental health and wellbeing definitions (mood, anxiety, stress) and measures (self-reported feelings, medication use).

These limitations make it difficult to draw firm conclusions about the actual impact of the ecosystem services on health and the related economic benefits. Further, it prevents comparisons between studies. Therefore, caution should be applied in interpreting the results.

A further methodological issue lies with the use of associations between an exposure and an outcome. For example, living in areas with greater access to parks for physical activity does not necessarily equate with actual use of the parks. Some of the research included in this review attempted to respond to this issue by using surveys to determine levels of individual use of such areas (for example, surveys with park users about the amount of physical activity actually undertaken in that space). While for air filtration and local climate regulation, actual use of the green space may be less of an issue (as these ecosystem services affect the ambient surrounds, such that benefits are received in a more passive way), the association is still problematic if it cannot account for temporal issues such as changes of address (people moving in and out of the area, length of time in the area) or spatial issues such as amount of time spent in the home environment compared with the benefit that might be received from areas outside of the neighbourhood.

For this review, examination of the impact of social determinants (such as income, employment and education) on the relationship between environment and health were not included as they were outside the scope of this study. Many of the studies accounted for neighbourhood level disadvantage by adjusting for area-level socioeconomic status in their analyses. In addition, several studies highlighted that differences in green space access and quality affect equitable access to the health protective effect of the ecosystem services. The importance of social determinants is clear, and future work could include a focus on these in the provision of ecosystem services and the benefit to health of the socially disadvantaged.

The choice of search terms was deliberately non-specific, as this was an extensive (though not exhaustive) exploration of the relationship between the 3 ecosystem services and health and provided a good basis for investigation of key issues. However, as with any review process, it is possible that the use of alternative or additional terms, or different search engines, could have resulted in additional articles being retrieved. Alternative search approaches (such as excluding the term 'ecosystem services' from the search strategy, or including terms such as 'green space') were not used, as these tended to return a large amount of literature relating to green space and health, but which did not attribute the health benefits to the specific ecosystem service.

There is a plethora of evidence showing that green space and nature provide multiple benefits to human health, both locally in Australia, and internationally. However, this review seeks to go a step further by investigating the contribution to the health benefits via specific ecosystem services pathways, in order to inform the development of ecosystem accounts, in line with the SEEA EA framework. While including other terms would potentially further benefit the review findings, the selection of studies reviewed nonetheless collates an extensive collection of important information on the current state of evidence specifically relating to the contribution of selected ecosystem services to health.

A future consideration, now that the health benefits relating to the 3 ecosystem services have been explored, would be to conduct a systematic review to produce robust estimates of the size, and potential economic benefits, of the health benefits in the Australian context. Systematic reviews use an empirical methodology to assess all available relevant literature on a subject, and which can assess the quality of the available evidence using clearly defined grading criteria, to make sound recommendations for use in policy and implementation settings. They are particularly useful in the field of epidemiology, where many of the studies are observational in nature, as was the case with the studies included in this review. Assessing the quality of the evidence helps to overcome some of the uncertainty around observed associations and causality that arises due to the limitations mentioned earlier in this discussion. Additionally, this systematic approach can help to identify types of data used to quantify health benefits of these ecosystem services, and therefore inform appropriate data sources and inputs in the Australian setting. Once these robust estimates of effect are determined, and appropriate local data sources are identified, Burden of Disease methodology and expertise can be applied to quantify the cost of the health benefits most strongly linked to each of the ecosystem services. While these steps were beyond the scope of this review, they are recommended here as important and practical steps, with potential to inform the SEEA EA on the health benefits of air filtration, local climate regulation and recreation-related ecosystem services.

6.2 Future steps

This review is an important first step in bringing together a broad range of relevant information on the health benefits offered by 3 ecosystem services. It identifies health benefits, measurement approaches, possible data sources and, in some cases, economic impacts. It provides a comprehensive and descriptive overview of the topic, upon which further work can be based.

Useful future steps would include the following:

- conducting a systematic review and level of evidence analysis – to provide evidence-based recommendations on which measures of ecosystem service provide the greatest benefits for risk factors and health conditions, and which data sources and inputs are most commonly used to measure this
- identifying relevant data sources and inputs available in the Australian context, and identifying data gaps that would benefit from data development
- conducting a Burden of Disease analysis – to quantify the size of the health impact and associated economic costs of health impacts from air filtration, local climate regulation and recreation-related ecosystem services.

Appendix A: Ecosystem services

Table A1: Description of ecosystem services as used in the System of Environmental Economic Accounts Ecosystem Accounts

Ecosystem service	
Provisioning services	
Biomass provisioning services	Crop provisioning services
	Grazed biomass provisioning services
	Livestock provisioning services
	Aquaculture provisioning services
	Wood provisioning services
	Wild fish and other natural aquatic biomass provisioning services
	Wild animals, plants and other biomass provisioning services
Genetic material services	
Water supply	
Other provisioning services	
Regulating and maintenance services	
Global climate regulation services	
Rainfall pattern regulation services (at sub-continental scale)	
Local (micro and meso) climate regulation services	
Air filtration services	
Soil quality regulation services	
Soil and sediment retention services	Soil erosion control services
	Landslide mitigation services
Solid waste remediation services	
Water purification services	Retention and breakdown of nutrients
	Retention and breakdown of other pollutants

(continued)

Table A1 (continued): Description of ecosystem services as used in the System of Environmental Economic Accounts Ecosystem Accounts

Regulating and maintenance services	
Water flow regulation services	Baseline flow maintenance services
	Peak flow mitigation services
Flood control services	Coastal protection services
	River flood mitigation services
Storm mitigation services	
Noise attenuation services	
Pollination services	
Biological control services	Pest control services
	Disease control services
Nursery population and habitat maintenance services	
Other regulating and maintenance services	
Cultural services	
Recreation-related services	
Visual amenity services	
Education, scientific and research services	
Spiritual, artistic and symbolic services	
Other cultural services	
Flows related to non-use values	
Ecosystem and species appreciation	

Appendix B: Summary of eligible articles, by ecosystem service

Table B1: Air filtration – summary of articles

Reference	Study type	Location	Setting	Sample size	Exposures	Health variables
Agay-Shay et al. 2019	Birth cohort study	Tel-Aviv, Israel	Urban	73,221 live births	Green space (NDVI), access to outdoor fitness equipment, air pollution exposure (NO_2, PM2.5) during pregnancy	Birthweight.
Anabitarte et al. 2020	Cohort study	Spain	Urban	441 pregnant women	Green space availability, residential NO_2 concentrations	Birthweight, low birthweight, prematurity, small for gestational age, and large for gestational age.
Capotorti et al. 2019	Case study	Rome, Italy	Urban	n.a.	Biodiversity and green infrastructure in urban spaces	n.a.
Chen 2020	Systematic review	Various	Various	10 publications	Urban nature exposure, air pollution	Cardiovascular disease; physical activity; mortality; Alzheimer's; acute bronchitis; acute myocardial infarction; acute respiratory symptoms; asthma exacerbation; chronic bronchitis; emergency room visits; hospital admissions related to cardiovascular, respiratory and lower respiratory symptoms; work loss days; birthweight, ADHD.
Chiabai et al. 2018	Literature review and framework development	Various	Urban	25 studies	Green space	Reduction in cardiovascular and respiratory conditions, stroke mortality.
Cochran et al. 2019	Framework development	United States	Various	n.a.	%PM10 removed annually by tree cover, % high-speed streets bordered by >25% tree buffer	Respiratory health, COPD.
Coutts and Hahn 2015	Systematic review	Various	Various	n.a.	Green infrastructure	Avoided mortality, acute respiratory symptoms, childhood asthma, cardiovascular and lower respiratory mortality.
Cusack et al. 2018	Birth cohort study	Toronto, Winnipeg, Edmonton and Vancouver, Canada	Urban	2,510 births	Green space (NDVI), proximity to neighbourhood park, neighbourhood walkability during pregnancy, air pollution (NO_2, O_3, PM2.5)	Birthweight.
Dadvand et al. 2015	Observational study	Barcelona, Spain	Urban	2,593 school children	Exposure to green space	Cognitive development.

(continued)

Table B1 (continued): Air filtration – summary of articles

Reference	Study type	Location	Setting	Sample size	Exposures	Health variables
de Jesus Crespo and Fulford 2018	Review and causal criteria analysis	Various	Various	212 studies	Green space	Gastro-intestinal disease, heat morbidity, cardiovascular disease and respiratory disease.
Dzhambov et al. 2019	Data used from 2 cross-sectional studies	Tyrol region (Austria/Italy)	Alpine/ Rural	1,091 total participants in both utilised studies	Normalized Difference Vegetation Index (NDVI), road/railway traffic noise, air pollution (NO_2)	Birthweight, low birthweight, pre-term birth and small for gestational age.
E Almeida et al. 2020	Observational study	Uberaba County, Brazil	Urban	Air monitoring at 5 schools, 340 questionnaire responses	Air quality (NO_2, O_3, PM10)	Child respiratory morbidity (symptoms including wheezing, sneezing, running nose, tearing and itchy eyes).
Endreney et al. 2017	Modelling study	Various (10 cities with a greater than a 10-million-person population)	Urban	n.a.	Tree cover, air pollution, climate energy use, CO, NO_2, PM10, SO_2	n.a.
Engemann et al. 2020a	Cohort study	Denmark	Various	943,027 people	Land cover type (determined by Copernicus Land Monitoring Service – CORINE – categorised as agricultural, near-natural green space, blue space, urban), vegetation density (NDVI), air pollution (primary particles, secondary inorganic particles, NO_2, O_3, SO_4)	Schizophrenia.
Feng and Astell-Burt 2017	Cross-sectional study	Australia	Various	4447 children	Perceived traffic volume in residential area, green space identified as ‘parkland’ in residential meshblocks	Asthma.
Gopalakrishnan et al. 2018	Modelling study	United States	Various	n.a.	Air pollution, grasslands and shrublands	Acute respiratory symptoms; emergency room visits and hospital admissions for respiratory illness, asthma exacerbations, acute/chronic bronchitis, acute myocardial infarction, other cardiovascular disease.
James et al. 2016	Cohort study	United States	Various	108,630 female adults	Vegetation	All-cause mortality (non-accidental), cause-specific mortality.

(continued)

Table B1 (continued): Air filtration – summary of articles

Reference	Study type	Location	Setting	Sample size	Exposures	Health variables
Kumar et al. 2019	Critical evaluation/systematic review	Various	Various	n.a.	Air pollution, green infrastructure	Cardiovascular disease, stroke, diabetes, overall mortality, circulatory disease, obesity, asthma, other respiratory disease, immune function and childhood cognitive development.
Laurent et al. 2019	Cohort study	California, United States	Various	72,632 low birthweight infants (cases), 5 controls per case	Maternal residential green space (NDVI), maternal exposure to air pollution (NO_2, O_3, PM2.5, elemental carbon)	Low birthweight.
Lee et al. 2021	Retrospective cohort study	Taiwan	Urban	16,184 births	Particulate matter air pollution, greenness exposure	Pre-term birth, term low birthweight, small for gestational age, birthweight and head circumference.
Liao et al. 2019	Prospective cohort study	Wuhan, China	Urban	6,807 pregnant women	Residential green space (NDVI)	Maternal glucose levels, impaired glucose tolerance, gestational diabetes mellitus.
Nie et al. 2020	Case control study	21 cities in southern China	Urban	8,042 cases and 6,887 controls	Maternal exposure to residential greenness	Congenital heart defects in babies.
Nowak et al. 2014	Modelling study	United States	Various	n.a.	Air pollution, tree coverage	All-cause mortality, acute respiratory symptoms.
Nowak et al. 2018	Modelling study	86 Canadian cities	Urban	n.a.	Air pollution, tree coverage	Acute bronchitis; acute myocardial infarction; acute respiratory symptoms; asthma exacerbation; chronic bronchitis; emergency room visits; hospital admissions for cardiovascular and respiratory conditions; lower respiratory symptoms; mortality; school loss days; upper respiratory symptoms; work loss days.

(continued)

Table B1 (continued): Air filtration – summary of articles

Reference	Study type	Location	Setting	Sample size	Exposures	Health variables
Paulin et al. 2020	Modelling study	the Netherlands	Various	n.a.	Air quality, vegetation, particulate matter, physical activity, urban cooling, water storage, green space, wind speed	Reduced health costs, reduced mortality.
Remme et al. 2015	Case study	Limburg, the Netherlands	Various	n.a.	Crop production, fodder production, drinking water production, air quality regulation, carbon sequestration, nature tourism and hunting	Cardiac hospital admission, lower respiratory symptoms in children and adults, medication/bronchodilator use in children and adults, new case chronic bronchitis, respiratory hospital admission, work loss days.
Salmond et al. 2016	Framework review	Various	Urban	n.a.	Tree coverage, street trees, urban forests	Allergic rhinitis, exacerbation of asthma, eczema, general human health.
Shen and Lung 2016	Observational (mediation analysis)	Taipei, Taiwan	Various (district)	48 districts	Temperature, air pollution (CO, NO_x, PM10, SO_2,), green space (landscape proportion, aggregation, fragmentation, patch distance, patch percentage, derived from landscape metrics)	Cardiovascular mortality (aortic aneurysms and dissection, hypertensive disease).
Sun et al. 2020	Modelling study	California	Various	All births between 2001–2008	Maternal exposure to residential green space and air pollution	Pre-term birth.
Tapsuwan et al. 2021	Cost–benefit analysis	Australia	Urban	419,192	Air pollution	Avoided health care costs (not specified).
Weber et al. 2021	Population based case-control study	San Joaquin Valley, California	Various	77,406 women	Maternal exposure to green space, air pollution and neighbourhood factors	Pre-eclampsia.
Wolf et al. 2020	Scoping review	Various	Various	n.a.	Air pollution, ultraviolet radiation, heat exposure, pollen, tree coverage exposure	Attention restoration, mental health, stress reduction and clinical outcomes.
Yang et al. 2019	Cross-sectional study	China	Urban	24,845 people	Community greenness	Blood pressure.

n.a. = not available (indicates where the information cannot be derived from the article).

ADHD = attention deficit hyperactivity disorder; COPD = chronic obstructive pulmonary disease; NDVI = normalized difference vegetation index.

Note: Sample size in terms of health outcome was included where possible; otherwise, sample size corresponds with spatial units or number of studies (for reviews).

Table B2: Local climate regulation – summary of articles

Reference	Study type	Location	Setting	Sample size	Exposures	Health variables
Boumans et al. 2014	Modelling	Austin, Texas	Various (census block, watershed)	696 (census blocks)	Temperature (air, surface), i-Tree vue (tree cover, impervious area), humidity, wind speed, green space (NDVI)	Heat-related emergency department visits and emergency medical service calls due to environmental exposures, mortality (non-accidental, cardiovascular-related).
Burkart et al. 2016	Observational (time series)	Lisbon, Portugal	Urban (civil parish)	218,764	Air pollution (O_3, PM10), temperature (land-surface temperature, equivalent temperature), green space (NDVI), blue space (proximity to water)	Mortality (all cause) (age 65 and over).
Benita et al. 2019	Observational (field experiment)	Singapore	Urban ('points of interest')	10,464	Temperature (air), noise, humidity, daylight, green space (park land cover), blue space (water body land cover)	Self-reported momentary happiness.
Benmarhnia et al. 2017	Observational (hot spot)	France, Paris	Urban (census block)	1,238	Temperature (air), percentage green space (vegetation via land cover map), air pollution (NO_2, PM2.5, PM10)	Mortality (all-cause) (age 65 and over).
Chen et al. 2014	Modelling	Melbourne, Australia	Urban (district)	n.a.	Temperature (air, building), humidity, solar irradiance, wind speed, air pollution, green space (various vegetation land covers)	Mortality (category not specified).
Cheng et al. 2021	Observational (field experiment)	Jiangsu Province, China	Urban (urban park)	Approx. 560,000 (posts)	Temperature (surface), air quality, green space (NDVI, urban park area), blue space (proportion of water area), imperviousness	Expressed happiness.

(continued)

Table B2 (continued): Local climate regulation – summary of articles

Reference	Study type	Location	Setting	Sample size	Exposures	Health variables
Chiabai et al. 2018	Literature review and framework development	Various	Urban	25 studies	Green space	Allergies, blood pressure, CHD, cortisol levels, CVD, 5-year survival rate, heart rate, infant mortality, life expectancy, 'persistence of disease', self-report health/wellbeing, stroke, various birth outcomes.
Choi et al. 2021	Observational (time series)	North Carolina, United States	Various (county)	1,208,766 (deaths)	Green space (NDVI), air pollution (PM 2.5), temperature (estimated air)	Mortality (all cause excluding external)
Dang et al. 2018	Observational (time series)	Ho Chi Minh City, Vietnam	Urban (district)	101,897 (mortalities)	Temperature (air), humidity, wind (speed, direction), air pressure, green space (vegetation land cover via satellite, urban canopy model – UCM)	Mortality (category not specified).
de Jesus Crespo and Fulford 2018	Review and causal criteria analysis	Various	Various	212 studies	Green space, temperature (heat hazard), air (clean air)	CVD, gastro-intestinal disease, heat-related morbidities, respiratory illness.
Denpetkul and Phosri 2021	Observational (case-crossover)	Thailand	Various (province, metropolitan)	2,891,407 (deaths)	Green space (NDVI), temperature (air/ambient), relative humidity	Mortality (all-cause, cardiovascular, respiratory).
Gascon et al. 2016	Systematic review and meta-analysis	Various	Various	12 studies	Green space	Mortality (all cause, cardiovascular, circulatory disease, heart disease, lung cancer, respiratory, stroke).
Goggins et al. 2012	Observational (time series)	Hong Kong	Urban (tertiary planning unit)	248 (tertiary planning units)	Temperature (air), green space (NDVI), wind speed, air pollution (NO_2, O_3, PM10, SO_2), humidity, solar radiation	Mortality (all-natural), non-cancer mortality.
Goggins et al. 2013	Observational (time series)	Kaohsiung, Taiwan	Various (district)	11 (districts)	Green/blue space (UCM), temperature (air), relative humidity, air pollution (CO, NO_2, O_3, SO_2, PM10)	Mortality (all natural and non-accidental).
Graham et al. 2016	Observational (hot spot)	Toronto, Canada	Urban (census tract)	2,709 (ambulance calls)	Temperature (air), green space (tree canopy land cover)	Ambulance calls.

(continued)

Table B2 (continued): Local climate regulation – summary of articles

Reference	Study type	Location	Setting	Sample size	Exposures	Health variables
Gronlund et al. 2015	Observational (case-crossover)	Michigan, United States	Urban (postcode)	n.a.	Temperature (air, apparent), dew point, ozone, green space (land cover map)	Mortality (all-cause, cardiovascular, heat-related, respiratory) (age 65 and over).
Gronlund et al. 2016	Observational (case-crossover)	Various (109 United States cities)	Various (postcode)	8,200 (postcodes)	Temperature (air), non-green space (non-water/vegetation land cover map)	Hospital admissions (non-respiratory – renal, heat; respiratory disease) (age 65 and over).
Harlan et al. 2013	Observational (hot spot)	Maricopa County, Arizona	Various (census block)	455 (deaths)	Temperature (surface), green space (NDVI)	Mortality (heat-related: effects of heat/light, 'environ', exhaustion, exposure to excessive natural heat, heat stress, heat stroke, hyperthermia).
He et al. 2020	Observational (case-crossover)	Various (multiple regions, Thailand)	Various (province)	59,836 (deaths)	Temperature, humidity, green space (NDVI)	Diabetes mortality.
Heaviside et al. 2017	Review	Various	Various	n.a.	Green space, temperature (heat)	Cardiovascular outcomes, morbidities, mortality.
Ho and Wong 2019	Observational (cross-sectional)	Hong Kong	Urban (tertiary planning units)	133,359 (deaths) 26,736 (cardiovascular), 28,703 (respiratory), 2,653 (mental/behavioural)	Green space (vegetation cover by land cover map), temperature (air), air pollution (NO_2, O_3, PM10, SO_2)	Mortality (all-cause, cardiovascular, mental/behavioural, respiratory).
Jang et al. 2020	Observational (time series)	Seoul, Korea	Urban (districts)	51 (districts)	Green space (urban forest, crop-field, woodland, via land cover map and satellite), impervious area, temperature (air/surface)	Mortality (all-cause).
Jennings and Gaither 2015	Review	Various	Various	n.a.	Green space, temperature (heat)	Cardiovascular outcomes, heat-related illness, obesity, psychological health.
Kabisch et al. 2017	Systematic review	Various	various	27 studies	Green space, air pollution, noise, temperature (heat)	Children: allergic sensitisation/asthma, childhood overweight, infant mortality, mental health. Elderly: cancer, CVD, mental health/wellbeing, mortality (all-cause, respiratory), respiratory disease.

(continued)

Table B2 (continued): Local climate regulation – summary of articles

Reference	Study type	Location	Setting	Sample size	Exposures	Health variables
Kim and Kim 2017	Observational (case-crossover)	Seoul, Korea	Urban (district / gu)	33,554 (deaths)	Green space (park area per person, green area, green area around buildings, rooftop green area), temperature (air), air pollution (PM10)	Mortality (all cause excluding accidental).
Kolokotsa et al. 2020	Qualitative review	Various	Various	2 case studies (relevant for green/blue space and temperature)	Green space, temperature, air pollution	Mortality.
Kua et al. 2021	Systematic review and meta-analysis	Various	Various	20 studies (11 in meta-analysis)	Green space (NDVI and various other measures)	Mortality (all-cause, chronic lower respiratory disease, CVD, diabetes, disease of the circulatory system, heat, ischemic heart disease, lung cancer, non-accidental, maternal, respiratory disease).
Ma et al. 2014	Observational (time series)	China (various cities)	Urban (city)	17 (cities)	Green space (metric not provided), temperature (air), relative humidity, air pollution (NO_2, PM10, SO_2)	Mortality (cardiovascular, non-accidental, respiratory).
Madrigano et al. 2013	Observational (case-crossover)	Worcester, Massachusetts	Urban (census tract, census block)	4,765 (2,427 mortalities)	temperature (air), dew point, ozone, air pollution (PM2.5), green space (NDVI), blue space (water bodies)	Acute myocardial infarction, angina, atrial fibrillation, cardiogenic shock, diabetes, family history of CHD, heart failure, hypertension, mortality (all-cause), smoking status, stroke.
Morais et al. 2021	Observational (hot spot)	Lisbon, Portugal	Urban (parish)	n.a.	Temperature (physiological equivalent temperature), green space (NDVI, street trees, cooling potential), imperviousness	Mortality (circulatory, respiratory) (age 65 and over).
Murage et al. 2020	Observational (case- crossover)	London	Urban (postcode, lower super output area)	185,397 (deaths)	Green space (NDVI, tree count and proportion domestic garden via land cover map), temperature (air)	Mortality (all cause).

(continued)

Table B2 (continued): Local climate regulation – summary of articles

Reference	Study type	Location	Setting	Sample size	Exposures	Health variables
Nyelele et al. 2019	Modelling	New York, United States	Urban (census block)	1,132 (census blocks)	i-Tree cool (air temperature reductions), i-Tree eco (air pollution via PM2.5, carbon storage and sequestration), i-Tree hydro (stormwater run-off reduction), green space (land cover map)	Mortality (cardiovascular, respiratory, pulmonary-related)
Pascal et al. 2021	Observational (time series)	Paris	Various (municipality)	601,643 (deaths)	Temperature (air), (lack of) green space (land cover map), (lack of) tree canopy (satellite), proportion impervious surface	Mortality (all cause).
Qiu et al. 2021	Observational (case-crossover)	Jiangsu, Guangdong, Liaoning, China	Various (province)	21,775 (population)	Temperature (air), dew point, green space (NDVI)	Mortality (all-cause) (age 65 and over).
Rosenthal et al. 2014	Observational (hot spot)	New York City	Urban (district, united hospital fund)	Approx.150,000	Temperature (ambient, surface), humidity, green space (trees and vegetation based on land cover map), imperviousness	Asthma, diabetes, hypertension (age 65 and over), mental distress, mortality (natural cause), obesity, self-reported general health, social isolation.
Sera et al. 2019	Observational (time series)	Global (340 cities over 22 countries)	Various (city, country)	50 million+ (deaths)	Temperature (ambient), air pollution (NO_2, PM2.5), green space (vegetation land cover map), region classification (urban, rural)	Hospital bed rates, mortality (all-cause, non-external cause).
Schinasi et al. 2020	Observational (case-crossover)	Philadelphia, Pennsylvania	Urban (census tract)	1,522 (deaths)	Green space (NDVI, tree canopy cover and grass/shrubs via land cover map), temperature (air)	Mortality (infant deaths).
Shen and Lung 2016	Observational (mediation analysis)	Taipei, Taiwan	Various (district)	48 districts	Temperature, air pollution (CO, NO_2, NO_x, PM10, SO_2), green space (landscape proportion, aggregation, fragmentation, patch distance, patch percentage, derived from landscape metrics)	Mortality (cardiovascular – aortic aneurysm and dissection, hypertensive disease).

(continued)

Table B2 (continued): Local climate regulation – summary of articles

Reference	Study type	Location	Setting	Sample size	Exposures	Health variables
Sinha et al. 2021	Modelling	Baltimore, Maryland USA	Urban (census block)	653 (census blocks)	i-Tree cool air (air temperature, dew point, wind speed, precipitation, solar radiation), ozone, green space (tree land cover via land cover map), imperviousness	Mortality (all-cause, cardiorespiratory, cardiovascular disease, pneumonia, stroke) (all ages, age 65 and over)
Smith et al. 2021	Review and meta-analysis	Various	Various	25 studies (14 in meta-analysis)	Blue space	Birth outcomes, depression and anxiety, general health, health related quality of life, mental health, mortality, obesity, psychological distress, restorative.
Son et al. 2016	Observational (time series)	Seoul, Korea	Various (gu / district)	25 gus / districts	Temperature (ambient), humidity, air pollution (O_3, PM10), green space (NDVI)	Mortality (all-cause, not including external cause).
Stone et al. 2014	Modelling	Atlanta (Georgia), Philadelphia (Pennsylvania), Phoenix (Arizona), United States	Various (census tract)	n.a.	Temperature (ambient, surface), humidity, radiation, wind velocity, green space (vegetation land cover map), surface reflectivity, imperviousness	Mortality (all-cause, non-accidental).
Ueijo et al. 2011	Observational (hot spot)	Phoenix, Arizona; Philadelphia	Urban (census block)	63 (deaths), 637 (heat distress calls)	Temperature (surface), green space (NDVI), imperviousness	Heat-related distress calls, mortality (heat-related).
Venter et al. 2020	Observational and modelling	Oslo, Norway	Urban (census tract)	Approx. 30,000 (at risk patients)	Temperature (air, surface), green space (NDVI, tree canopy data, land cover map), imperviousness	Heat-stress related health problems (diagnoses under circulatory, general, nervous system and skin categories).
White et al. 2020	Qualitative review and conceptual framework	Various	Various	n.a.	Blue space, temperature (heat), noise, air pollution	Mortality, mental health/wellbeing.

(continued)

Table B2 (continued): Local climate regulation – summary of articles

Reference	Study type	Location	Setting	Sample size	Exposures	Health variables
Wolf et al. 2020	Scoping review and framework	Various	various	201 studies	Green space	Heat-related morbidity/mortality, thermal comfort (changes in skin temperature).
Xu et al. 2013	Observational (case crossover)	Barcelona	Urban (census tract)	52,806 (deaths)	Temperature (apparent), green space (tree land cover)	Mortality (all-cause).
Xu et al. 2019a	Observational (case-crossover and case-only)	Brisbane, Australia	Urban (unit not provided)	10,542 (hospitalisations), 513 (deaths)	Green space (NDVI), temperature (air), air pollution (NO_2, PM10)	Hospitalisations (diabetes), mortality (diabetes).
Xu et al. 2019b	Observational (case-crossover and case only)	Brisbane, Australia	Urban (unit not provided)	907 (hospitalisations), 307 (deaths)	Green space (NDVI), temperature (air), air pollution (NO_2, PM10)	Hospitalisations (Alzheimer's), mortality (Alzheimer's).
Zanobetti et al. 2013	Observational (case only)	Various (135 United States cities)	Various (postcode)	7,204,031 (deaths)	Temperature (air, apparent), dew point, green space (land cover map), blue space (land cover map), water vapour pressure	Atrial fibrillation, Alzheimer's, congestive heart failure, COPD, dementia, diabetes, mortality (all-cause), Parkinson's, pneumonia.
Zhang et al. 2021	Observational (prospective cohort)	China	Various (province)	20,758 (deaths)	Green space (NDVI), temperature (air), air pollution (PM2.5)	Mortality (all-cause).

n.a. = not available (indicates where the sample size could not be derived from the article).

CHD = coronary heart disease; COPD = chronic obstructive pulmonary disease; CVD = cardiovascular disease; NDVI = normalized difference vegetation index; UCM = urban canopy model.

Note: Sample size in terms of health outcome was included where possible; otherwise, sample size corresponds with spatial units or number of studies (for reviews).

Table B3: Recreation-related ecosystem services – summary of articles

Reference	Study type	Location	Setting	Sample size	Exposures	Health variables
Agay-Shay et al. 2019	Birth cohort study	Tel-Aviv, Israel	Urban	73,221 live births	Green space (NDVI) access to outdoor fitness equipment, air pollution exposure (NO_2, PM2.5) during pregnancy	Birthweight.
Andersen et al. 2021	Systematic review	Various	Natural environments and forests	33 studies (20 on humans)	Outdoor nature, activities in nature where no or light physical activity took place such as forest bathing	Immune system function.
Buckley and Brough 2017	Literature review	United Kingdom	Various	n.a.	Nature, parks, adventure and eco therapy interventions for mental health – for example, green prescriptions	Mental health.
Cusack et al. 2018	Birth cohort study	Toronto, Winnipeg, Edmonton and Vancouver, Canada	Urban	2,510 births	Green space (NDVI), proximity to neighbourhood park, neighbourhood walkability during pregnancy	Birthweight.
Fagerholm et al. 2021	Case study (survey based)	Turku, Finland	Urban	730 people aged 15 and over	Outdoor recreation sites	Subjective wellbeing.
Gascon et al. 2017	Systematic review	Various	Various	35 studies	Outdoor blue spaces	Cardiovascular health, general health, mental health and wellbeing, obesity, physical activity.
Georgiou et al. 2021	Systematic review and meta-analysis	Various	Various	50 studies	Residential proximity to blue space	‘Health’, with physical activity, restoration (includes stress, anxiety, depression), social interaction and environmental factors as mediating pathways.
Grilli and Sacchelli 2020	Literature review, various locations and settings	Various	Forests	36 studies	Forests	Stress relief and relaxation, mental wellbeing.

(continued)

Table B3 (continued): Recreation-related ecosystem services – summary of articles

Reference	Study type	Location	Setting	Sample size	Exposures	Health variables
Henke and Petropoulos 2013	GIS-based exploratory research study	Wales, United Kingdom	All outdoor areas of Wales with potential for recreational	n.a.	Outdoor recreational areas, such as nature reserves, national trails, registered historic parks and gardens, cycle networks etc.	Death rates, life expectancy, limiting long term illness, physical activity.
Hussain et al. 2019	Observational study	Austria, Switzerland	Alpine meadows	22 adults	Meadows of differing levels of biodiversity (managed and abandoned meadows)	Blood pressure, stress reduction.
Jimenez et al. 2021	Narrative review	Various	Various	n.a.	General nature exposure	Anxiety, brain activity, cardiovascular disease, cognitive function, depression, diabetes, mental health, mood/emotions ('affective state'), physical activity, sleep, stress.
Joung et al. 2020	Single group cross-over study, South Korea, Chukreong Mountain (case) and the Daejeon metropolitan city (control)	South Korea	Forest (cases), urban (control)	24 college students	Walking in urban and forest areas	Anxiety, heart rate variability, mood, salivary cortisol.
Kobayashi et al. 2021	Experimental study	Japan	Forests areas, city areas	57 young women	Set walking courses of around 1 km for walking experiment and fixed viewing positions for 15-minute increments in the viewing experiment	Psychological (as measured by Profile Mood State, 6 sub-scales: Tension-Anxiety, Depression-Dejection, Anger-Hostility, Vigour, Fatigue, Confusion).
McEachan et al. 2015	Cohort study	Bradford, England, United Kingdom	Urban	7,547 pregnant women	Residential green space (NDVI) Physical activity	Depressive symptoms.
Mekala et al. 2015	Business case study	Melbourne, Australia	Urban	n.a.	Proposed Stony Creek Rehabilitation Project	Avoided health costs, physical inactivity.

(continued)

Table B3 (continued): Recreation-related ecosystem services – summary of articles

Reference	Study type	Location	Setting	Sample size	Exposures	Health variables
Moseley et al. 2018	Indicator development using survey data	England and Wales, United Kingdom	Rural and semi-rural woodland	2,659 adults	Activities undertaken in woodlands visits	QALY.
O'Brien and Forster 2021	Longitudinal survey	England, United Kingdom	Various	2,115 people aged 16 and older	Engagement with and visits to nature	Connectedness to nature, physical activity and wellbeing.
Richardson et al. 2013	Cross-sectional analysis of data	New Zealand	Urban	8,157 people aged 15 and older	Neighbourhood level green space availability determined via 3 land-used data sets that were amalgamated to produce classifications	CVD, physical activity, overweight, poor general health, poor mental health.
Sandifer et al. 2015	Literature review	Various	Various	n.a.	Various	Range of mental and physical health outcomes, including ADHD, anxiety, decreased type 2 diabetes, general health, quality of life, psychological wellbeing, reduced blood pressure, reduced COPD and other respiratory conditions, reduced cortisol levels.
Shanahan et al. 2016	Framework analysis	Brisbane, Australia	Urban	1,538 adults	Vegetation complexity measures applied to survey responses about frequency and average duration of outdoor green space visits	High blood pressure, depression, physical activity.
Smith et al. 2021	Systematic review and meta-analysis	Various	Urban	25 studies in review, 14 studies in synthesis	Blue spaces	Anxiety, birth outcomes, depression, general health, health related quality of life, mental health, mortality, obesity, psychological distress, restorative.
Song et al. 2013	Experimental study	Chiba, Japan	Urban	13 males	Pre-determined 15-minute walk courses in urban parks (case) and city areas (control)	Anxiety, heart rate, heart rate variability, mood.

(continued)

Table B3 (continued): Recreation-related ecosystem services – summary of articles

Reference	Study type	Location	Setting	Sample size	Exposures	Health variables
Sugiyama et al. 2008	Cross-sectional observational study	Adelaide, Australia	Urban	1,895 adults	Perceived neighbourhood greenness, walking for transport and recreation	Perceived physical and mental health.
Vert et al. 2019	Meta-analysis	Barcelona, Spain	Urban	973 surveyed park users, and total estimated annual cyclists (*n*= 1,030,000) and pedestrians (*n*= 1,070,000)	Urban riverside park development	All-cause mortality, disability adjusted life years, morbidity (breast and colon cancer, dementia, ischemic heart disease, ischemic stroke, type 2 diabetes), physical activity.
Vienneau et al. 2017	Modelling study	Switzerland	National	4.2 million people	Residential greenness, determined by NDVI and land use classification data	All-natural cause mortality, cardiovascular mortality, respiratory mortality.
White et al. 2016	Cross-sectional analysis of survey data	England, United Kingdom	Various	8.23 million adults	Outdoor environments, activity type, physical activity levels	Population health gains (measured by level of activity) in QALY.
Wood et al. 2017	Analysis of RESIDE Project (longitudinal natural experiment) data	Perth, Western Australia	Urban	492 adults	Digital spatial (polygon) database of location and spatial extent of all parks and other green open spaces across the Perth metropolitan region	Mental wellbeing.
Zhang et al. 2018	Cross-sectional study	Guanzhou, China	Urban (‘megacity’)	1,003 adults	‘Activity space’ collected via survey, green space exposure assessment based on the proportion of time at different activity locations	Mental health, physical health, social health.

n.a. = not available (indicates where the sample size could not be derived from the article).

ADHD = attention deficit hyperactivity disorder; COPD = chronic obstructive pulmonary disease; CVD = cardiovascular disease; NDVI = normalized difference vegetation index; QALY = Quality Adjusted Life Years; RESIDE project = RESIDential Environments project.

Note: Sample size in terms of health outcome was included where possible; otherwise, sample size corresponds with the number of studies (for reviews).

Appendix C

Table C1: List of health conditions included in analysis by Nowak et al. 2014

Pollutant	Health effect
PM2.5 (particulate matter measured as particles of less than 2.5 microns (PM2.5) in diameter)	Acute bronchitis
	Acute myocardial infarction (non-fatal)
	Acute respiratory symptoms (minor restricted activity days)
	Asthma exacerbations (cough / shortness of breath / wheeze)
	Chronic bronchitis
	Emergency room visits (asthma)
	Cardiovascular hospital admissions (less myocardial infarctions)
	Respiratory hospital admissions (all / lower respiratory symptoms)
	Mortality (all-cause)
	Upper respiratory symptoms
	Work loss days
NO_2 (nitrogen dioxide)	Acute respiratory symptoms (cough)
	Asthma exacerbations (missed school days / slow play / one or more symptoms)
	Emergency room visits, respiratory (asthma)
	Hospital admissions (all respiratory)
O_3 (ozone)	Acute respiratory symptoms (minor restricted activity days)
	Emergency room visits, respiratory (asthma)
	Mortality (all-cause)
	Respiratory hospital admissions (all respiratory)
	School loss days (all cause)
SO_2 (suphur dioxide)	Asthma exacerbation (slow play, missed school days, one or more symptoms)
	Acute respiratory symptoms (cough)
	Emergency room visits, respiratory (asthma)
	Respiratory hospital admissions (all respiratory)

Note: Table adapted from Table 1, Nowak et al. 2014.

Appendix D

Table D1: Modelling studies and scenarios modelled – local climate regulation

Reference / model	Model scenario
Boumans et al. (2014)	Scenario 1: tree cover doubling in developed land areas
Various	Scenario 2: 15% new trees planted in forest coverage where none currently exists
Chen et al. (2014) UCM-TAPM	Scenario 1: 100% forest coverage
	Scenario 2: 100% shrub-land coverage
	Scenario 3: 100% grassland
	Scenario 4: 49% urban (leafy)
	Scenario 5: 38% urban (generic)
	Scenario 6: 15% CBD (65% building coverage)
	Scenario 7: CBD (one-third vegetation)
	Scenario 8: CBD (double vegetation)
	Scenario 9: CBD (50% green roof)
	Scenario 10: CBD (double vegetation + 50% green roof)
Nyelele et al. (2019) i-Tree	Scenario 1: no tree mortality between 2010 and 2030
	Scenario 2: 4% annual tree mortality between 2010 and 2030
	Scenario 3: 8% annual tree mortality between 2010 and 2030
Sinha et al. (2021) i-Tree BenMAP	Scenario 1: increase existing tree coverage by 10% in each area unit
	Scenario 2: remove 10% of existing tree coverage
	Scenario 3: remove all existing tree coverage
Stone et al. (2014) BenMAP	Scenario 1: all commercial roofs converted to grass and surface paving and building roofs overlaid with tree canopy or converted to grass/shrubs
	Scenario 2: 50% of all roadway surfaces overlaid by tree canopy, and grass or barren land in public parcels converted to tree canopy, and barren or agricultural land in public parcels converted to a grass/shrub mix
	Scenario 3: all building roofs converted to highly reflective impervious surfaces
	Scenario 4: all roads, parking lots, and surface paving converted to moderately reflective impervious surfaces
	Scenario 5: combination of scenario 1 and scenario 2
	Scenario 6: combination of scenario 3 and scenario 4
	Scenario 7: combination of scenario 1–4
Venter et al. (2020) n.a.	Scenario 1: all trees are removed

n.a. = not available (indicates where the model was not identified in the article).

CBD = central business district; TAPM = the air pollution model; UCM = urban canopy model.

Acknowledgements

The former Department of Agriculture, Water and the Environment (now the Department of Climate Change, Energy, the Environment and Water) funded this review.

Georgie Amoyal, Lizzie Gorrell, Dr Brendan Hutchinson and Lucinda Macdonald of the Prevention and Environmental Health Unit, Australian Institute of Health and Welfare wrote this review, under the guidance of Richard Juckes, Dr Vanessa Prescott and Claire Sparke. Jenna Haddin, Sarah Jones, Micaella Watson and Dr David Wong provided assistance. Special thanks to Geoff Callaghan, Vergil Dolar, Melanie Dunford and Dr Tuan Phan for their input on health economics and burden of disease, and to Dr Fadwa Al-Yaman for her Aboriginal and Torres Strait Islander expertise.

The authors would also like to thank the following people for their expert review and valuable feedback: Department of Agriculture, Water and the Environment; Dr Suzi Bond (Australian Bureau of Statistics); Associate Professor Xiaoqi Feng (University of New South Wales); Distinguished Professor Billie Giles-Corti (RMIT University); Professor Yuming Guo (Monash University); Terry Hills (Department of the Prime Minister and Cabinet); Professor Sotiris Vardoulakis (Australian National University).

Abbreviations

ADHD	attention deficit and hyperactivity disorder
AIHW	Australian Institute of Health and Welfare
BenMAP	Benefits Mapping and Analysis Program
BMI	body mass index
BVOC	biogenic volatile organic compounds
CBD	central business district
CO	carbon monoxide
COPD	chronic obstructive pulmonary disease
CORINE	Copernicus Land Monitoring Service
DALY	disability adjusted life years
DAWE	Department of Agriculture, Water and the Environment
DCCEEW	Department of Climate Change, Energy, the Environment and Water
GDM	gestational diabetes mellitus
HR	hazard ratio
IGT	impaired glucose tolerance
IWM	integrated water management

MRS-VOLY	Maximum Societal Revenue Value of Statistical Life Year
NDVI	normalized difference vegetation index
NHS	National Health Service
NICE	National Institute for Health and Care Excellence
NO	nitric oxide
NO_x	nitrogen oxides
NO_2	nitrogen dioxide
O_3	ozone
OECD	Organisation for Economic Co-operation and Development
OR	odds ratio
PAF	population attributable fraction
PM	particulate matter
PM2.5	particulate matter measured as particles of less than 2.5 microns in diameter
PM10	particulate matter measured as particles of less than 10 microns in diameter
QALY	Quality Adjusted Life Years
RR	rate ratio, relative risk
SEEA	System of Environmental Economic Accounting
SEEA CF	System of Environmental Economic Accounting Central Framework
SEEA EA	System of Environmental Economic Accounts Ecosystem Accounts
SF-12 (MCS)	12-Item Short Form, Mental Component Score
SO_2	sulphur dioxide
STAI	State Trait Anxiety Inventory
UCM	urban canopy model
UHI	urban heat island
VOC	volatile organic compounds
VOLY	Value of Statistical Life Year
WHO-5	World Health Organization’s Five Wellbeing Indexes
YLD	years of life lived with disability
YLL	years of life lost

Symbols

>	greater than
<	less than
A$	Australian dollar
C$	Canadian dollar
€	Euro
£	Pound Sterling
US$	United States dollar
kg	kilogram
m	metre
mmHG	millimetre of mercury
n	number
n.a.	not available, not applicable

Glossary

Aboriginal or Torres Strait Islander: A person who identifies themselves as being of Aboriginal or Torres Strait Islander origin.

acute: A term that describes something that comes on sharply and is often brief, intense and severe.

air filtration services: 'Ecosystem contributions to the filtering air-borne pollutants through the deposition, uptake, fixing and storage of pollutants by ecosystem components, particularly plants, that mitigates the harmful effects of the pollutants' (United Nations et al. 2021:132).

air pollution: Substances present in the air that have harmful effects or are toxic to those inhaling them.

all-cause mortality: The death rate from all causes of death for a population in a given time period.

allergenic: A term that describes something causing allergies.

allergic rhinitis: A bodily response triggered by an allergic reaction. The symptoms may include a runny or blocked nose and/or sneezing and watery eyes. Also known as 'hay fever'. See also **rhinitis**.

Alzheimer's: A degenerative brain disease caused by nerve cell death, resulting in shrinkage of the brain. A common form of **dementia**.

ambient air pollution: Outdoor air pollution.

ambient temperature: The temperature of the surrounding air.

angina: Temporary chest pain or discomfort when the heart's own blood supply is inadequate to meet extra needs, as in exercise.

aortic aneurysm and dissection: A condition in which a tear occurs in the main artery of the body, the aorta. Blood rushing through the tear can cause the aorta to split, or dissect, which may lead to death.

asthma: A common, chronic inflammatory disease of the air passages that presents as episodes of wheezing, breathlessness and chest tightness due to widespread narrowing of the airways and obstruction of airflow.

atrial fibrillation: A disturbance of the electrical system of the heart, which results in an uneven and fast heartbeat.

avoided damages cost: The cost of the damage that would occur if that ecosystem service was absent.

biodiversity: The variety of all living organisms on earth, including plants, animals and micro-organisms, and the land and water-based ecosystems of which they are a part.

biogenic volatile organic compounds: See **volatile organic compounds**.

blood pressure: The force exerted by the blood on the walls of the arteries as it is pumped around the body by the heart. It is written, for example, as 134/70 mmHg, where the upper number is the systolic pressure (the maximum force against the arteries as the heart muscle contracts to pump the blood out) and the lower number is the diastolic pressure (the minimum force against the arteries as the heart relaxes and fills again with blood). Levels of blood pressure can vary greatly from person to person and from moment to moment in the same person.

blue space: A consensus definition of 'blue space' does not yet exist. Common definitions in research include 'areas dominated by surface waterbodies or watercourses' (Gunawardena et al. 2017), 'outdoor environments – either natural or manmade – that prominently feature water and are accessible to humans' (Grellier et al. 2017), and 'all forms of natural and manmade surface water' (Smith et al. 2021).

bronchitis: Inflammation of the main air passages (bronchi). May be acute or chronic.

bronchodilator: A type of medication that dilates the airways, hence, increasing airflow to and from the lungs. Bronchodilators can be either short-acting or long-acting; short-acting bronchodilators are often referred to as 'relievers'.

burden of disease: The quantified impact of a disease or injury on a population using the **disability-adjusted life years (DALY)** measure.

cancer: A large range of diseases where some of the body's cells become defective, begin to multiply out of control, invade and damage the area around them, and can then spread to other parts of the body to cause further damage.

canopy: The above-ground portion of a vegetation type, formed by plant crowns. In a woodland or forest, the canopy is formed by the crowns of trees and sometimes large shrubs. The canopy can be further divided into upper, mid and lower canopy layers. The tallest plants of a vegetation type form the upper canopy layer.

cardiogenic shock: A life-threatening condition where the heart is unable to pump enough blood to vital organs.

cardiorespiratory: A descriptive term relating to the heart and the lungs.

cardiovascular disease: Any disease of the circulatory system, namely the heart (cardio) or blood vessels (vascular). Includes **angina**, heart attack and **stroke.** Also known as circulatory disease.

cerebrovascular disease: Any disorder of the blood vessels supplying the brain or its covering membranes. A notable and major form of cerebrovascular disease is **stroke**.

chronic obstructive pulmonary disease (COPD): Serious, progressive and disabling long-term lung disease where damage to the lungs (usually because of both emphysema and chronic bronchitis) obstructs oxygen intake and causes increasing shortness of breath.

confounder / confounding variable: A variable other than the one being studied that is associated with both the exposure and the outcome, and which distorts (or 'confounds') the association between the variables being studied.

congenital: A condition that is recognised at birth, or is believed to have been present since birth, including conditions inherited or caused by environmental factors.

congestive heart failure: A condition that occurs when the heart functions less effectively in pumping blood around the body. It can result from a wide variety of diseases and conditions that can impair or overload the heart, such as heart attack, other conditions that damage the heart muscle directly, high **blood pressure**, or a damaged heart valve.

coronary heart disease: A disease due to blockages in the heart's own (coronary) arteries, expressed as **angina** or a heart attack. Also known as ischaemic heart disease.

cortisol: A hormone produced by the adrenal glands in response to stress.

COVID-19 pandemic: The pandemic caused by COVID-19, a disease caused by the new coronavirus SARS-CoV-2. It is a major health threat and international crisis, which has led to substantial disruption to almost all parts of society worldwide. The outbreak first came to international notice through a cluster of unexplained pneumonia cases in Wuhan, China, in late December 2019. The COVID-19 epidemic was declared a pandemic (the worldwide spread of a new infectious disease) by the World Health Organization on 11 March 2020.

dementia: A term used to describe a group of similar conditions characterised by the gradual impairment of brain function. It is commonly associated with memory loss, but can affect speech, cognition (thought), behaviour and mobility. An individual's personality may also change, and their health and functional ability decline as the condition progresses. Dementia is a fatal condition.

demographics: Statistical data relating to population groups, such as age, sex, economic status, education level and employment status, among others.

depression: A mood disorder with prolonged feelings of being sad, hopeless, low and inadequate, with a loss of interest or pleasure in activities and often with suicidal thoughts or self-blame.

diabetes (diabetes mellitus): A chronic condition where the body cannot properly use its main energy source – the sugar glucose. This is due to a relative or absolute deficiency in insulin, a hormone produced by the pancreas that helps glucose enter the body's cells from the bloodstream and be processed by them. Diabetes is marked by an abnormal build-up of glucose in the blood; it can have serious short- and long-term effects.

diastolic blood pressure: See 'blood pressure'.

disability-adjusted life years (DALY): A measure of healthy life lost, either through premature death or living with disability due to illness or injury.

ecosystem disservices: The effects of nature that negatively affect human health and wellbeing. For example, certain types of trees produce pollens that cause asthma and other respiratory conditions.

ecosystem services: 'The contributions of ecosystems to the benefits that are used in economic and other human activity' (United Nations et al. 2021:121).

elemental carbon: An air pollutant produced by the incomplete combustion of fossil fuels. It is a primary pollutant and occurs as soot.

environmental economic accounts: Accounts showing the link between the environment and the economy, presented in physical and monetary terms – for example, extraction of natural resources, their use in the economy, changes in natural stock levels during a set period, and economic activity related to the environment.

evapotranspiration: The process of heat transfer from the urban surface to the atmosphere via evaporation of water and transpiration from vegetation.

fibrosis: Thickening or scarring of tissue, usually in response to injury or chronic inflammation.

forest bathing: A form of recreation originating in Japan that involves connecting with nature through experiencing the forest atmosphere. Also known as *Shinrin-yoku,* it is considered both a physiological and psychological experience.

gestation: Another term for pregnancy.

gestational diabetes mellitus (GDM): A form of **diabetes** that is first diagnosed during pregnancy (gestation). It may disappear after pregnancy but signals a high risk of diabetes occurring later.

green space: Areas of public and private land, such as nature reserves, public parks, residential gardens, sporting facilities, beachfronts and waterways.

hazard ratio: A statistical measure of risk that is the ratio of how often an event occurs in one group compared with how often it occurs in another group, over a period of time.

health: 'A state of complete physical, mental and social well-being and not merely the absence of disease or infirmity' (WHO 1946:2).

hypertension: A well-accepted definition (as definitions vary) is from the World Health Organization: a systolic blood pressure of 140 mmHg or more or a diastolic blood pressure of 90 mmHg or more, or if [the person is] receiving medication for high blood pressure. Also known as high **blood pressure**.

immunomodulation: The modulation, or adjustment, of the immune system in response to exposure to a substance that stimulates or suppresses it.

impaired glucose tolerance (IGT): A condition in which blood glucose levels are higher than normal but less than required for a diagnosis of diabetes, and which signals an increased risk of developing type 2 diabetes.

incidence: The number of new cases (of an illness, injury or event, and so on) occurring during a given period. Compare with **prevalence**.

integrated water management: A collaborative approach (among a range of organisations) to the development and management of all elements of the water cycle, including waterways, management of wastewater, drinking water, stormwater and water treatment, which considers economic, social and environmental benefits (Agarwal et al. 2000; DELWP 2017).

ischaemic stroke: A type of stroke due to a reduced or blocked supply of blood in the brain. Also known as cerebral infarction

life expectancy: An indication of how long a person can expect to live, depending on the age they have already reached. Technically, it is the number of years of life left to a person at a particular age if death rates do not change. The most commonly used measure is life expectancy at birth.

local climate regulation services: 'The ecosystem contributions to the regulation of ambient atmospheric conditions (including micro and mesoscale climates) through the presence of vegetation that improves the living conditions for people and supports economic production' (United Nations et al. 2021:132).

low birthweight: The weight of a baby at birth that is less than 2,500 g.

lower respiratory infections: Infections of the lower respiratory tract, such as pneumonia or bronchiolitis. Also referred to as lower respiratory tract infections.

meta-analysis: A statistical analytical method for determining a quantitative estimate of a topic, by combining data from multiple independent studies on the same topic.

morbidity: Ill health in an individual, and levels of ill health in a population or group.

mortality: The number or rate of deaths in a population during a given time period.

myocardial infarction: A heart attack.

natural killer cells: The cells that are part of the body's immune response that help to protect against disease through their ability to kill abnormal cells, such as tumour cells.

obesity: A marked degree of overweight, defined for population studies as a body mass index of 30.00 kg/m^2 or more. See also **overweight**.

odds ratio (OR): The ratio of 2 odds is a measure of risk, telling us how much more likely it is that someone who is exposed to the factor under study will develop a particular outcome compared with someone who is not exposed.

overweight: Defined for the purpose of population studies as a body mass index of 25 or more See also **obesity**.

PM2.5: Atmospheric particulate matter (PM) that have a diameter of less than 2.5 micrometres (0.0025 millimetres).

PM10: Atmospheric particulate matter (PM) that have a diameter of less than 10 micrometres (0.010 millimetres).

passive smoking: The act of breathing in smoke from other people's cigarettes or other tobacco products (such as pipes or cigars).

percentile: The value on a scale of 1 to 100 that indicates the percentage of a distribution equal to or below it. For example, 95% of values in the distribution lie below the 95th percentile, and 5% of values lie above it.

perinatal: A term pertaining to, or occurring in, the period shortly before or after birth (usually up to 28 days after).

photochemical pollution: Air pollution caused by the action of sunlight on nitrogen oxides and hydrocarbons, such as those found in traffic-generated exhaust. Considered a secondary air pollutant, as it is converted from one form to another.

pneumonia: Inflammation of the lungs as a response to infection by bacteria or viruses. The air sacs become flooded with fluid, and inflammatory cells and affected areas of the lung become solid. Pneumonia is often quite rapid in onset and marked by a high fever, headache, cough, chest pain and shortness of breath.

population attributable fraction: The proportion of a particular disease that could have been avoided if the population had never been exposed to a risk factor.

pre-eclampsia: A condition that complicates pregnancy and is characterised by high blood pressure, fluid retention and protein in the urine. The placental function may be compromised.

pre-term birth: A birth before 37 completed weeks of gestation.

prevalence: The number or proportion (of cases, instances, and so forth) in a population at a given time. Compare with **incidence**.

quality-adjusted life years (QALY): The number of years of life saved as a result of the intervention, adjusting for the quality of life during those years. One quality adjusted life year is equal to one year of life lived in perfect health.

quartile: A group derived by ranking the population or area according to specified criteria and dividing it into 4 equal parts, each containing a quarter of the population or area.

rate ratio (RR): The ratio of 2 rates or proportions is a measure used to compare rates between different population groups, regions, age groups, sexes or time periods. It is also known as 'relative risk' in some epidemiological studies (that is, the risk of developing a disease relative to exposure). Also known as **relative risk**.

recreation-related ecosystem services: 'The ecosystem contributions, in particular through the biophysical characteristics and qualities of ecosystems, that enable people to use and enjoy the environment through direct, in-situ, physical and experiential interactions with the environment' (United Nations et al. 2021:133).

relative risk (RR): See **rate ratio**.

renal: A term relating to the kidney.

respiratory: A term relating to the airways and lungs.

rhinitis: See **allergic rhinitis.**

risk factor: Any factor that represents a greater risk of a health condition or health event. For example, smoking, alcohol use, high body mass index.

schizophrenia: A complex disorder of brain function in which a person experiences an altered perception of reality, and which affects the person's thoughts, perceptions emotions and behaviours.

socioeconomic: A term relating to the social standing of an individual or group, often based on combined measures of education, income and occupation.

stroke: An event that occurs when an artery supplying blood to the brain suddenly becomes blocked or bleeds. A stroke often causes paralysis of parts of the body normally controlled by that area of the brain, or speech problems and other symptoms. It is a major form of cerebrovascular disease.

structural equation modelling: A set of statistical techniques used to test and evaluate hypothesised causal relationships by analysing the impact of unobserved variables (or 'latent' variables) on outcome variables.

subcutaneous: A term describing beneath the skin.

System of Environmental Economic Accounting (SEEA): An international standard for environmental–economic accounting. The SEEA is a framework for organising and presenting environmental statistics and their relationship with the economy. It is based on internationally agreed standard concepts, accounting rules and so on. There are specific SEEA accounts for each of the following:

- agriculture, forests and fisheries
- air emissions
- energy
- environmental activity
- ecosystems
- land
- material flow (that is, the physical inputs into an economy, material accumulation in the economy, and outputs to other economies). It balances other data sets and accounts, such as forestry, water, air emissions accounts etc.)
- water.

System of Environmental Economic Accounting Ecosystem Accounting (SEEA EA): A framework for organising, measuring, tracking changes in and valuing ecosystems, with the purpose of making the contributions of nature to the economy and humans visible (United Nations et al. 2021).

systolic blood pressure: See **blood pressure.**

tertile: A group derived by ranking the population or area according to specified criteria and dividing it into 3 equal parts, each containing a third of the population or area.

thermoregulation: A component of homeostasis that refers to the body's capacity to regulate its own temperature to remain within a certain range, even when the temperature of the surrounding environment changes.

trimester: One of the 3 periods of 3 months during pregnancy, usually divided into the first, second and third trimesters.

type 2 diabetes: The most common form of **diabetes**, occurring mostly in people aged 40 and over, and marked by reduced or less effective insulin.

upper respiratory symptoms: Symptoms, usually resulting from an infection, that affect the upper parts of the respiratory tract, including the nose, sinus, throat and large airways. Symptoms include a runny nose, sore throat, sneezing and coughing.

Value of Statistical Life (VSL): An estimate of the amount of money that a person or society would be willing to pay to save one human life. This is an anonymous life, rather than a specific person's life, and hence is referred to as a 'statistical life'.

Value of Statistical Life Year (VOLY): An estimate of the amount of money that a person or society would be willing to pay for one additional year of life. This is an anonymous life, rather than a specific person's life, and hence is referred to as a 'statistical life'.

volatile organic compounds (VOCs): Carbon-based chemicals that readily evaporate at room temperature. Biogenic VOCs (bVOCs) are produced and released into the atmosphere by plants.

wellbeing: A state of health, happiness and contentment. It can also be described as judging life positively and feeling good. For public health purposes, physical wellbeing (for example, feeling very healthy and full of energy) is also viewed as critical to overall wellbeing. Because wellbeing is subjective, it is typically measured with self-reports, but objective indicators (such as household income, unemployment levels and neighbourhood crime) can also be used.

YLD (years lived with a disability): The number of years of what could have been a healthy life that were instead spent in states of less than full health. YLD represent non-fatal burden.

YLL (years of life lost): The number of years of life lost due to premature death, defined as dying before the ideal life span. YLL represent fatal burden.

References

Abram NJ, Henley BJ, Sen Gupta A, Lippmann TJR, Clarke H, Dowdy AJ et al. (2021) 'Connections of climate change and variability to large and extreme forest fires in southeast Australia', *Communications Earth and Environment*, 2(8), doi:10.1038/s43247-020-00065-8.

ABS (Australian Bureau of Statistics) (2022) *Regional population* (reference period 2020–21), ABS, Australian Government, accessed 22 June 2022, https://www.abs.gov.au/statistics/people/population/regional-population/latest-release.

Agarwal A, de los Angeles MS, Bhatia R, Chéret I, Davila-Poblete S, Falkenmark M et al. (2000) *Integrated water resources management*, GWP–TAC background paper no. 4, Global Water Partnership, Stockholm.

Agay-Shay K, Michael Y, Basagaña X, Martínez-Solanas È, Broday D, Lensky IM et al. (2019) 'Mean and variance of greenness and pregnancy outcomes in Tel Aviv during 2000–14: longitudinal and cross-sectional approaches', *International Journal of Epidemiology*, 48(4):1054–72, doi:10.1093/ije/dyy249.

AIHW (Australian Institute of Health and Welfare) (2010) *Monitoring the impact of air pollution on asthma in Australia: a methods paper*, AIHW, Australian Government, accessed 19 May 2022, https://www.aihw.gov.au/reports/chronic-respiratory-conditions/monitoring-impact-air-pollution-on-asthma/summary.

—— (2020a) *Burden of disease overview*, AIHW, Australian Government, accessed 11 October 2021, https://www.aihw.gov.au/reports-data/health-conditions-disability-deaths/burden-of-disease/overview.

—— (2020b) *Insufficient physical activity*, AIHW, Australian Government, accessed 23 August 2021, https://www.aihw.gov.au/reports/risk-factors/insufficient-physical-activity/contents/insufficient-physical-activity.

—— (2020c) *What is health?*, AIHW, Australian Government, accessed 28 September 2021, https://www.aihw.gov.au/reports/australias-health/what-is-health.

—— (2021a) *Australian Burden of Disease Study 2018: impact and causes of illness and death in Australia 2018*, AIHW, Australian Government, accessed 19 May 2022, https://www.aihw.gov.au/reports/burden-of-disease/abds-impact-and-causes-of-illness-and-death-in-aus/summary.

—— (2021b) *Australian Burden of Disease Study 2018 – key findings*, AIHW, Australian Government, accessed 19 May 2022, https://www.aihw.gov.au/reports/burden-of-disease/burden-of-disease-study-2018-key-findings/contents/about.

—— (2021c) *Disease expenditure in Australia 2018–19*, AIHW, Australian Government, accessed 23 May 2022, https://www.aihw.gov.au/reports/health-welfare-expenditure/disease-expenditure-australia/contents/summary.

—— (2021d) *Understanding welfare and wellbeing*, accessed 18 August 2021, AIHW, Australian Government, https://www.aihw.gov.au/reports/australias-welfare/understanding-welfare-and-wellbeing.

—— (2022a) *Health system spending per case of disease and for certain risk factors*, AIHW, Australian Government, accessed 18 May 2022, https://www.aihw.gov.au/reports/health-welfare-expenditure/health-system-spending-per-case-of-disease.

—— (2022b) International health data comparisons, AIHW, Australian Government, accessed 2 August 2022, https://www.aihw.gov.au/reports/international-comparisons/international-health-data-comparisons.

Alcock I, White M, Cherrie M, Wheeler B, Taylor J, McInnes R et al. (2017) 'Land cover and air pollution are associated with asthma hospitalisations: a cross-sectional study', *Environment international*, 109:29–41, doi:10.1016/j.envint.2017.08.009.

Anabitarte A, Subiza-Pérez M, Ibarluzea J, Azkona K, García-Baquero G, Miralles-Guasch C et al. (2020) 'Testing the multiple pathways of residential greenness to pregnancy outcomes model in a sample of pregnant women in the metropolitan area of Donostia-San Sebastian', *International Journal of Environmental Research and Public Health*, 17(12):4520, doi:10.3390/ijerph17124520.

Andersen L, Corazon SS and Stigsdottir UK (2021) 'Nature exposure and its effects of immune system functioning: a systematic review', *International Journal of Environmental Research and Public Health*, 18(4):1416, doi:10.3390/ijerph18041416.

Anselmi L, Binyaruka P and Borghi J (2017) 'Understanding causal pathways within health systems policy evaluation through mediation analysis: an application to payment for performance (P4P) in Tanzania', *Implementation Science*, 12:10, doi:10.1186/s13012-016-0540-1.

Astell-Burt T and Feng X (2019) 'Association of urban green space with mental health and general health among adults in Australia', *JAMA Network Open*, 2(7):e198209, doi:10.1001/jamanetworkopen.2019.8209.

—— (2020) 'Urban green space, tree canopy and prevention of cardiometabolic diseases: a multilevel longitudinal study of 46 786 Australians', *International Journal of Epidemiology*, 49(3):926–933, doi:10.1093/ije/dyz239.

—— (2022) 'Paths through the woods', *International Journal of Epidemiology*, 51(1):1–5, doi:10.1093/ije/dyab233.

Bark RH, Barber M, Jackson S, Maclean K, Pollino C and Moggridge B (2019) 'Operationalising the ecosystem services approach in water planning: a case study of Indigenous cultural values from the Murray-Darling Basin, Australia' *International Journal of Biodiversity Science, Ecosystem Services and Management*, 11(3):239–249, doi:10.1080/21513732.2014.983549.

Barton DN, Obst C, Day B, Caparrós A, Dadvand P, Fenichel E Havinga I et al. (2019) *Discussion paper 10: Recreation services from ecosystems*, paper submitted to the Expert Meeting on Advancing the Measurement of Ecosystem Services for Ecosystem Accounting, New York, 22–24 January 2019 and subsequently revised version of 25 March 2019, accessed 19 May 2022, https://seea.un.org/events/expert-meeting-advancing-measurement-ecosystem-services-ecosystem-accounting.

Bateson T and Schwartz J (2008) 'Children's response to air pollutants', *Journal of Toxicology and Environmental Health*, 71(3):238–243, doi:10.1080/15287390701598234.

Beale S, Bending M and Trueman P (2007) *An economic analysis of environmental interventions that promote physical activity*, York Health Economics Consortium, University of York.

Bech P, Olsen LR, Kjoller M and Rasmussen NK (2003) 'Measuring well-being rather than the absence of distress symptoms: a comparison of the SF-36 Mental Health subscale and the WHO-Five Well-Being Scale', *The International Journal of Methods in Psychiatric Research* 12(2): 85–91, doi:10.1002/mpr.145.

Beggs PJ, Zhang Y, Bambrick H, Berry HL, Linnenluecke MK, Trueck S et al. (2019) 'The 2019 report of the MJA–Lancet countdown on health and climate change: a turbulent year with mixed progress', *Medical Journal of Australia*, 211(11):490–491, doi:10.5694/mja2.50405.

Beil K and Hanes D (2013) 'The influence of urban natural and built environments on physiological and psychological measures of stress – a pilot study', *International Journal of Environmental Research and Public Health*,10(4):1250–1267, doi:10.3390/ijerph10041250.

Bell JF, Wilson JS and Liu GC (2008) 'Neighborhood greenness and 2-year changes in body mass index of children and youth', *American Journal of Preventive Medicine*, 35(6):547–53, doi:10.1016/j.amepre.2008.07.006.

Bell SL, Leyshon C, Foley R and Kearns RA (2019) 'The "healthy dose" of nature: a cautionary tale', *Geography Compass*,13(1):e12415, doi:10.1111/gec3.12415.

Benita F, Bansal G and Tunçer B (2019) 'Public spaces and happiness: evidence from a large-scale field experiment', *Health and Place*, 56: 9–18, doi:10.1016/j.healthplace.2019.01.014.

Benmarhnia T, Kihal-Talantikite W, Ragettli MS and Deguen S (2017), 'Small-area spatiotemporal analysis of heatwave impacts on elderly mortality in Paris: a cluster analysis approach', *Science of the Total Environment*, 592:288–294, doi:10.1016/j.scitotenv.2017.03.102.

Bentayeb M, Simoni M, Baiz N, Norback D, Baldacci S, Maio S et al. (2012) 'Geriatric Study in Europe on Health Effects of Air Quality in Nursing Homes (GERIE) Group: adverse respiratory effects of outdoor air pollution in the elderly', *International Journal of Tuberculosis and Lung Disease*, 16(9):1149–1161, doi:10.5588/ijtld.11.0666.

Beyer KM, Kaltenbach A, Szabo A, Bogar S, Nieto FJ and Malecki KM (2014) 'Exposure to neighborhood green space and mental health: evidence from the survey of the health of Wisconsin', *International Journal of Environmental Research and Public Health*, 11(3): 3453–72, doi:10.3390/ijerph110303453.

BITRE (Bureau of Infrastructure, Transport and Regional Economics) (2019), *Road trauma Australia 2018: statistical summary*, BITRE, Department of Infrastructure, Transport, Cities and Regional Development, Australian Government, accessed 7 July 2022, https://www.bitre.gov.au/publications/ongoing/archived_road_deaths_australia_annual_summaries.

Bodicoat D, Dalton AM, O'Donovan G and Gray L (2014) 'The association between neighbourhood green space and type 2 diabetes in a large cross-sectional study', *BMJ Open*, 4(12):e006076, doi:10.1136/bmjopen-2014-006076.

Bohnenstengel SI, Evans S, Clark PA and Belcher SE (2011) 'Simulations of the London urban heat island', *Quarterly Journal of the Royal Meteorological Society* 137(659): 1625–1640, doi:10.1002/qj.855.

Borchers Arriagada N, Bowman DM, Palmer AJ and Johnston FH (2020) 'Climate change, wildfires, heatwaves and health impacts in Australia' in Akhtar R (ed.) *Extreme weather events and human health*, Springer, Cham, Switzerland, doi:10.1007/978-3-030-23773-8_8.

Botzen WJW, Martinius ML, Bröde P, Folkerts MA, Ignjacevic P, Estrada F et al. (2020) 'Economic valuation of climate change-induced mortality age dependent cold and heat mortality in the Netherlands', *Climatic Change*, 162:545–562, doi:10.1007/s10584-020-02797-0.

Boumans RJM, Phillips DL, Victery W and Fontaine TD (2014) ‘Developing a model for effects of climate change on human health and health-environment interactions: heat stress in Austin, Texas’, *Urban Climate*, 8:78–99 doi:10.1016/j.uclim.2014.03.001.

Bowler D, Buyung-Ali L, Knight TM and Pullin AS (2010a) ‘A systematic review of evidence for the added benefits to health of exposure to natural environments’, *BMC Public Health*, 10:456, doi:10.1186/1471-2458-10-456.

—— (2010b) ‘Urban greening to cool towns and cities: a systematic review of the empirical evidence’, *Landscape and Urban Planning*, 97(3), 147–155, doi:10.1016/j.landurbplan.2010.05.006.

Brook RD, Franklin B, Cascio W, Hong Y, Howard G, Lipsett M et al. (2004) ‘Air pollution and cardiovascular disease: a statement for healthcare professionals from the expert panel on population and prevention science of the American Heart Association’, *Circulation*, 109(21): 2655–2671, doi:10.1161/01.CIR.0000128587.30041.C8.

Brunekreef B and Holgate ST (2002) ‘Air pollution and health’, *The Lancet*, 360(9341): 1233–1242, doi:10.1016/S0140-6736(02)11274-8.

Buckley RC and Brough P (2017) ‘Economic value of parks via human mental health: an analytical framework’, *Frontiers in Ecology and Evolution*, 5:16, doi:10.3389/fevo.2017.00016.

Burkart K, Meier F, Schneider A, Breitner S, Canário P, Alcoforado MJ et al. (2016) ‘Modification of heat-related mortality in an elderly urban population by vegetation (urban green) and proximity to water (urban blue): evidence from Lisbon, Portugal’, *Environment Health Perspectives*, 124(7):927–934, doi:10.1289/ehp.1409529.

Capotorti G, Alós Ortí MM, Coplz R, Furaso L, Mollo B, Salvatori E and Zavattero L (2019) ‘Biodiversity and ecosystem services in urban green infrastructure planning: a case study from the metropolitan area of Rome, Italy’, *Urban Forestry and Urban Greening*, 37:87–96, doi:10.1016/j.ufug.2017.12.014.

Cariñanos P and Casares-Porcel M (2011) ‘Urban green zones and related pollen allergies: a review. Some guidelines for designing spaces of low allergy impact’, *Landscape and Urban Planning*, 101:205–214, doi:10.1016/j.landurbplan.2011.03.006.

Chameides WL, Lindsay RW, Richardson J and Kiang CS (1988) ‘The role of biogenic hydrocarbons in urban photochemical smog: Atlanta as a case study’, *Science*, 241(4872): 1473–1475, doi:10.1126/science.3420404.

Chen D, Wang X, Thatcher M, Barnett G, Kachenko A and Prince R (2014) ‘Urban vegetation for reducing heat related mortality’, *Environmental Pollution*, 192: 275–294, doi:10.1016/j.envpol.2014.05.002.

Chen X (2020) ‘Monetary valuation of urban nature’s health effects: a systematic review’, *Journal of Environmental Planning and Management*, 63(10):1716–1737, doi:10.1080/09640568.2019.1689107.

Cheng Y, Zhang J, Wei W and Zhao B (2021) ‘Effects of urban parks on residents’ expressed happiness before and during the COVID-19 pandemic’, *Landscape and Urban Planning*, 212:04118, doi:10.1016/j.landurbplan.2021.104118.

Chiabai A, Quiroga S, Martinez-Juarez P, Higgins S and Taylor T (2018) ‘The nexus between climate change, ecosystem services and human health: towards a conceptual framework’, *Science of the Total Environment*, 635:1191–1204, doi:10.1016/j.scitotenv.2018.03.323.

Cho KS, Lim YR, Lee K, Lee K, Lee JH and Lee IS (2017) ‘Terpenes from forests and human health’, *Toxicology Research*, 33(2):97–106, doi:10.5487/TR.2017.33.2.097.

Choi HM, Chen C, Son JY and Bell ML (2021) ‘Temperature-mortality relationship in North Carolina, USA: regional and urban-rural differences’, *Science of the Total Environment*, 787:147672, doi:10.1016/j.scitotenv.2021.147672.

Cissé G, McLeman R, Adams H, Aldunce P, Bowen K, Campbell-Lendrum D et al. (forthcoming 2022) ‘Health, wellbeing, and the changing structure of communities’, in Pörtner HO, Roberts DC, Tignor M, Poloczanska ES, Mintenbeck K, Alegría A et al. (eds) *Climate change 2022: impacts, adaptation, and vulnerability*, [Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change], Cambridge University Press, Cambridge.

Cochran F, Jackson L, Neale A, Lovette J and Tran L (2019) ‘A community EcoHealth index from EnviroAtlas ecosystem services metrics’, *International Journal of Environmental Research and Public Health*,16(15):2760, doi:10.3390/ijerph16152760.

Coombes E, Jones AP and Hillsdon M (2010) ‘The relationship of physical activity and overweight to objectively measured green space accessibility and use’, *Social Science and Medicine*, 70(6):816–22, doi:10.1016/j.socscimed.2009.11.020.

Costanza R, D’Arge R, de Groot R, Farber S, Grasso M, Hannon B et al. (1997) ‘The value of the world’s ecosystem services and natural capital’, *Nature*, 387:253–260, https://doi.org/10.1038/387253a0.

Coutts C and Hahn M (2015) ‘Green infrastructure, ecosystem services and human health’, *International Journal of Environmental Research and Public Health*, 12(8):9768–9798, doi:10.3390/ijerph120809768.

Cummins S and Fagg J (2012) ‘Does greener mean thinner? Associations between neighbourhood greenspace and weight status among adults in England’, *International Journal of Obesity*, 36(8):1108–13, doi:10.1038/ijo.2011.195.

Curran SL, Andrykowski MA and Studts JL (1995) ‘Short Form of the Profile of Mood States (POMS-SF): psychometric information’, *Psychological Assessment*, 7(1):80–83, doi:10.1037/1040-3590.7.1.80.

Cusack L, Sbihi H, Larkin A, Chow A, Brook JR, Moraes T et al. (2018) ‘Residential green space and pathways to term birth weight in the Canadian Healthy Infant Longitudinal Development (CHILD) Study’, *International Journal of Health Geographics*, 17(1):1–2, https://doi.org/10.1186/s12942-018-0160-x.

Dadvand P, Nieuwenhuijsen MJ, Esnaola M, Forns J, Basagaña X, Alvarez-Pedrerol M et al. (2015) ‘Green spaces and cognitive development in primary schoolchildren’, *Proceedings of the National Academy of Sciences of the United States of America*, 112(26):7937–7942, doi:10.1073/pnas.1503402112.

Dadvand P, Villanueva CM, Font-Ribera L, Martinez D, Basagaña X, Belmonte J et al. (2014) ‘Risks and benefits of green spaces for children: a cross-sectional study of associations with sedentary behavior, obesity, asthma, and allergy’, *Environmental Health Perspectives*, 122(12):1329–1335, doi:10.1289/ehp.1308038.

Dalton AM and Jones AP (2019) ‘Residential neighbourhood green space is associated with reduced risk of cardiovascular disease: a prospective cohort study’, *PLoS ONE*, 15(1):e0226524, doi:10.1371/journal.pone.0226524.

Dang TN, Van DQ, Kusaka H, Seposo XT and Honda Y (2018) 'Green space and deaths attributable to the urban heat island effect in Ho Chi Minh City', *American Journal of Public Health*, 108(S2):S137–S143, doi:10.2105/AJPH.2017.304123.

Daniel TC, Muhar A, Arnberger A, Aznar O, Boyd JW, Chan KM et al. (2012) 'Contributions of cultural services to the ecosystem services agenda', *Proceedings of the National Academy of Sciences of the United States of America*, 109(23):8812–8819, doi:10.1073/pnas.1114773109.

DAWE (Department of Agriculture, Water and the Environment) (2019) *Ecosystem accounts*, Department of Climate Change, Energy, the Environment and Water, Australian Government, accessed 18 October 2021, https://eea.environment.gov.au/accounts/ecosystem-accounts.

Dedman R (2011) 'Greening the west: a public health perspective', [presentation by Department of Health at the Think Tank for Greening the West project meeting, City West Water Office, Melbourne, Australia].

de Jesus Crespo and Fulford R (2018) 'Eco-Health linkages: assessing the role of ecosystem goods and services on human health using causal criteria analysis', *International Journal of Public Health*, 63(1):81–92, doi:10.1007/s00038-017-1020-3.

Dempsey S, Lyons S and Nolan A (2018) 'Urban green space and obesity in older adults: evidence from Ireland', *SSM – Population Health*, 4:206-15, doi:10.1016/j.ssmph.2018.01.002.

Denpetkul T and Phosri A (2021) 'Daily ambient temperature and mortality in Thailand: estimated effects, attributable risks, and effect modifications by greenness', *Science of the Total Environment*, 791:148373, doi:10.1016/j.scitotenv.2021.148373.

DELWP (Victorian Department of Environment, Land, Water and Planning) (2017) *Integrated water management framework for Victoria: an IWM approach to urban water planning and shared decision making throughout Victoria*, accessed 29 June 2022, https://www.water.vic.gov.au/liveable/integrated-water-management-program/iwm-framework.

Department of the Environment (2015) *National Clean Air Agreement: towards a clean air future for all Australian*s, Department of the Environment, Australian Government, https://www.awe.gov.au/environment/protection/air-quality/national-clean-air-agreement.

Department of Health (2021) National Preventive Health Strategy 2021–2030, Department of Health, Australian Government, accessed 17 March 2022, https://www.health.gov.au/resources/publications/national-preventive-health-strategy-2021-2030.

Diener A and Mudu P (2021) 'How can vegetation protect us from air pollution? A critical review on green spaces' mitigation abilities for air-borne particles from a public health perspective – with implications for urban planning', *Science of the Total Environment*, 796:148605, doi:10.1016/j.scitotenv.2021.148605.

Doick KJ, Atkinson G E, Cordle P and Giupponi N (2013) 'Investigating design and provision of access facilities as a barrier to woodland use', *Urban Forestry and Urban Greening*, 12(1):117–125, doi:10.1016/j.ufug.2012.12.001.

Donovan GH, Butry DT, Michael YL, Prestemon JP, Liebhold AM, Gatziolis D and Mao MY (2013) 'The relationship between trees and human health: evidence from the spread of the emerald ash borer', *American Journal of Preventive Medicine*, 44(2):139–45, doi:10.1016/j.amepre.2012.09.066.

Dzhambov AM, Markevych I and Lercher P (2019) 'Associations of residential greenness, traffic noise and air pollution with birth outcomes across alpine areas', *Science of the Total Environment*, 678:399–408, doi:10.1016/j.scitotenv.2019.05.019.

E Almeida LO, Favaro A, Raimundo-Costa W, Anhê ACBM, Ferreira DC, Blanes-Vidal V and Dos Santos Senhuk APM (2020) 'Influence of urban forest on traffic air pollution and children respiratory health', *Environmental Monitoring and Assessment*, 192(3):175, doi:10.1007/s10661-020-8142-4.

Endreny TA, Santagata R, Perna A, De Stefano C, Rallo RF and Ulgiati S (2017) 'Implementing and managing urban forests: a much needed conservation strategy to increase ecosystem services and urban wellbeing', *Ecological Modelling*, 360:328–335, doi:10.1016/j.ecolmodel.2017.07.016.

Engemann K, Pedersen CB, Arge L, Tsirogiannis C, Mortensen PB and Svenning JC (2018) 'Childhood exposure to green space – a novel risk-decreasing mechanism for schizophrenia?', *Schizophrenia Research*, 199:142–148, doi:10.1016/j.schres.2018.03.026.

Engemann K, Svenning JC, Arge L, Brandt J, Erikstrup C, Geels C et al. (2020a) 'Associations between growing up in natural environments and subsequent psychiatric disorders in Denmark', *Environmental Research*, 188:109788, doi:10.1016/j.envres.2020.109788.

Engemann K, Svenning JC, Arge L, Brandt J, Geels C, Mortensen PB et al. (2020b) 'Natural surroundings in childhood are associated with lower schizophrenia rates', *Schizophrenia Research*, 216:488–495, doi:10.1016/j.schres.2019.10.012.

Fagerholm N, Eiola S and Arki V (2021) 'Outdoor recreation and nature's contribution to well-being in a pandemic situation – case Turku, Finland', *Urban Forestry and Urban Greening* 64:127257, doi:10.1016/j.ufug.2021.127257.

Feng X and Astell-Burt T (2017) 'Is neighborhood green space protective against associations between child asthma, neighborhood traffic volume and perceived lack of area safety? Multilevel analysis of 4447 Australian children', *International Journal of Environmental Research and Public Health*, 14(5):543, doi:10.3390/ijerph14050543.

Fish R, Church A and Winter M (2015) 'Conceptualising cultural ecosystem services: a novel framework for research and critical engagement', *Ecosystem Services*, 21:208–217, doi:10.1016/j.ecoser.2016.09.002.

Frumkin H, Bratman GN, Breslow SJ, Cochran B, Kahn Jnr. PH, Lawler JJ et al. (2017) 'Nature contact and human health: a research agenda', *Environmental Health Perspectives*, 125(7):075001, doi:10.1289/EHP1663.

Gascon M, Triguero-Mas M, Martínez D, Dadvand P, Forns J, Plasència A and Nieuwenhuijsen MJ (2015) 'Mental health benefits of long-term exposure to residential green and blue spaces: a systematic review', *International Journal of Environmental Research and Public Health*, 12(4):4354–4379, doi:10.3390/ijerph120404354.

Gascon M, Triguero-Mas M, Martinez D, Dadvand P, Rojas-Rueda D, Plasencia A and Nieuwenhuijsen M (2016) 'Residential green spaces and mortality: a systematic review' *Environment International*, 86:60–67, doi:10.1016/j.envint.2015.10.013.

Gascon M, Zijlema W, Vert C, White MP and Nieuwenhuijsen M (2017) 'Outdoor blue spaces. Human health and well-being: a systematic review of qualitative studies', *International Journal of Hygiene and Environmental Health*, 220(8), doi:10.1016/j.ijheh.2017.08.004.

Gasparrini A, Guo Y, Hashizume M, Lavigne E, Zanobetti A, Schwartz J et al. (2015) ‘Mortality risk attributable to high and low ambient temperature: a multicountry observational study’, *The Lancet*, 386(9991):369–75, doi:10.1016/S0140-6736(14)62114-0.

GBD (Global Burden of Disease) 2019 Diseases and Injury Collaborators (2020) ‘Global burden of 369 diseases and injuries, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019’, *The Lancet*, doi:10.1016/S0140-6736(20)30925-9.

Georgiou M, Morison G, Smith N, Tieges and Chastin S (2021) ‘Mechanisms of impact of blue spaces on human health: a systematic literature review and meta-analysis’, *International Journal of Environmental Research and Public Health*, 18(5):2486, doi:10.3390/ijerph18052486.

Giles-Corti B, Bull F, Knuiman M, McCormack G, Van Niel K, Timperio A et al. (2013) ‘The influence of urban design on neighbourhood walking following residential relocation: longitudinal results from the RESIDE study’, *Social Science & Medicine*, 77:20–30, doi:10.1016/j.socscimed.2012.10.016.

Gładka A, Rymaszewska J and Zatoński T (2018) ‘Impact of air pollution on depression and suicide’, *International Journal of Occupational Medicine and Environmental Health*, 31(6):711–21, doi:10.13075/ijomeh.1896.01277.

Goggins WB, Chan EY, Ng E, Ren C and Chen L (2012) ‘Effect modification of the association between short-term meteorological factors and mortality by urban heat islands in Hong Kong’, *PLoS One*, 7(6):e38551, doi:10.1371/journal.pone.0038551.

Goggins WB, Ren C, Ng E, Yang C and Chan EY (2013) ‘Effect modification of the association between meteorological variables and mortality by urban climatic conditions in the tropical city of Kaohsiung, Taiwan’, *Geospatial Health*, 8(1):37–44, doi:10.4081/gh.2013.52.

Goldberg D (1972) *The detection of psychiatric illness by questionnaire*, Oxford University Press, Oxford.

Goldberg DP and Hillier VF (1979) ‘A scaled version of the General Health Questionnaire’, *Psychological Medicine*, 9(1):139–45, doi:10.1017/S0033291700021644.

Gopalakrishnan V, Hirabayashi S, Ziv G and Bakshi BR (2018) ‘Air quality and human health impacts of grasslands and shrublands in the United States’, *Atmospheric Environment*, 182:193–199, doi:10.1016/j.atmosenv.2018.03.039.

Graham D, Vanos J, Kenny N and Brown R (2016) ‘The relationship between neighbourhood tree canopy cover and heat-related ambulance calls during extreme heat events in Toronto, Canada’, *Urban Forestry and Urban Greening*, 20:180–186, doi:10.1016/j.ufug.2016.08.005.

Grellier J, White MP, Albin M, Bell S, Elliott LR, Gascón M et al. (2017) ‘BlueHealth: a study programme protocol for mapping and quantifying the potential benefits to public health and well-being from Europe’s blue spaces’, *BMJ Open*, 7(6):e016188, doi:10.1136/bmjopen-2017-016188.

Grilli G and Sacchelli S (2020) ‘Health benefits derived from forest: a review’, *International Journal of Environmental Research and Public Health*, 17(17):6125, doi:10.3390/ijerph17176125.

Gromke C and Blocken B (2015) ‘Influence of avenue-trees on air quality at the urban neighbourhood scale. Part: II: traffic pollutant concentrations at pedestrian level’, *Environmental Pollution*, 196:176–84, doi:10.1016/j.envpol.2014.10.015.

Gronlund C, Berrocal V, White-Newsome J, Conlon K and O'Neill M (2015) 'Vulnerability to extreme heat by socio-demographic characteristics and area green space among the elderly in Michigan, 1990–2007', *Environmental Research*, 136: 449–461, doi:10.1016/j.envres.2014.08.042.

Gronlund CJ, Zanobetti A, Wellenius GA, Schwartz JD and O'Neill MS (2016) 'Vulnerability to renal, heat and respiratory hospitalizations during extreme heat among U.S. elderly', *Climate Change*, 136(3):631–645, doi:10.1007/s10584-016-1638-9.

Gunawardena K, Wells M and Kershaw T (2017) 'Utilising green and blue space to mitigate urban heat island intensity', *Science of the Total Environment*, 584–585:1040–1055, doi:10.1016/j.scitotenv.2017.01.158.

Guo Y, Gasparrini A, Armstrong B, Li S, Tawatsuoa B, Tobias A et al. (2014) 'Global variation in the effects of ambient temperature on mortality: a systematic evaluation' *Epidemiology*, 25(6):781–789, doi:10.1097/EDE.0000000000000165.

Ha S, Hu H, Roussos-Ross D, Haidong K, Roth J and Xu X (2014) 'The effects of air pollution on adverse birth outcomes', *Environmental research*, 134:198–204, doi:10.1016/j.envres.2014.08.002.

Hahad O, Lelieveld J, Birklein F, Lieb K, Daiber A and Münzel T (2020) 'Ambient air pollution increases the risk of cerebrovascular and neuropsychiatric disorders through induction of inflammation and oxidative stress', *International Journal of Molecular Sciences*, 21(12):4306, doi:10.3390/ijms21124306.

Haines-Young R and Potschin M (2012) 'Common international classification of ecosystem services (CICES): consultation on version 4, August–December 2012', [report to the European Environment Agency, Centre for Environmental Management, University of Nottingham, United Kingdom].

Haluza D, Schönbauer R and Cervinka R (2014) 'Green perspectives for public health: a narrative review on the physiological effects of experiencing outdoor nature', *International Journal of Environmental Research and Public Health*, 11(5):5445-5461, doi:10.3390/ijerph110505445.

Harlan SL, Brazel AJ, Prashad L, Stefanov WL and Larsen L (2006) 'Neighborhood microclimates and vulnerability to heat stress', *Social Science & Medicine*, 63(11): 2847–2863, doi:10.1016/j.socscimed.2006.07.030.

Harlan S, Declet-Barreto J, Stefanov W and Petitti D (2013) 'Neighborhood effects on heat deaths: social and environmental predictors of vulnerability in Maricopa County, Arizona', *Environmental Health Perspectives*, 121(2):197–204, doi:10.1289/ehp.1104625.

Hartig T, Mitchell R, de Vries S and Frumkin H (2014) 'Nature and health', *Annual Review of Public Health*, 35:207–228, doi:10.1146/annurev-publhealth-032013-182443.

Hazer M, Formica MK, Dieterlen S and Morley CP (2018) 'The relationship between self-reported exposure to greenspace and human stress in Baltimore, MD', *Landscape and Urban Planning*, 169:47–56. doi:10.1016/j.landurbplan.2017.08.006.

He Y, Cheng L, Bao J, Deng S, Liao W, Wang Q et al. (2020) 'Geographical disparities in the impacts of heat on diabetes mortality and the protective role of greenness in Thailand: a nationwide case-crossover analysis', *Science of the Total Environment*, 711:135098, doi:10.1016/j.scitotenv.2019.135098.

Heaviside C, Macintyre H and Vardoulakis S (2017) 'The urban heat island: implications for health in a changing environment', *Current Environmental Health Reports*, 4(3):296–305, doi:10.1007/s40572-017-0150-3.

Helbich M, Klein N, Roberts H, Hagedoorn P and Groenewegen PP (2018) 'More green space is related to less antidepressant prescription rates in the Netherlands: a Bayesian geo-additive quantile regression approach', *Environmental Research*, 166:290–297, doi:10.1016/j.envres.2018.06.010.

Henke JM and Petropoulos GP (2013) 'A GIS-based exploration of the relationships between human health, social deprivation and ecosystem services: the case of Wales, UK', *Applied Geography*, 45:77–88, doi:10.1016/j.apgeog.2013.07.022.

Hidano T, Fukuhara M, Iwawaki M, Soga S and Spielberger CD (2000) *State-Trait Anxiety Inventory (Form JYZ) Test Manual*, [Japanese adaptation of the State Trait Anxiety Inventor], Jitsumu-Kyoiku Syuppan, Tokyo.

Ho HC and Wong MS (2019) 'Urban environmental influences on the temperature–mortality relationship associated mental disorders and cardiorespiratory diseases during normal summer days in a subtropical city', *Environmental Science and Pollution Research*, 26(23):24272–24285, doi:10.1007/s11356-019-05594-0.

Hodan WB and Barnard WR (2004) 'Evaluating the contribution of PM2.5 precursor gases and re-entrained road emissions to mobile source PM2.5 particulate matter emissions', [MACTEC Under Contract to the Federal Highway Administration], accessed 2 September 2021, https://www3.epa.gov/ttnchie1/conference/ei13/mobile/hodan.pdf.

Holland I, DeVille NV, Browning MHEM, Buehler RM, Hart JE, Hipp JA et al. (2021) 'Measuring nature contact: a narrative review', *International Journal of Environmental Research and Public Health*, 18(8):4092, doi:10.3390/ijerph18084092.

Hooper LG and Kaufman JD (2018) 'Ambient air pollution and clinical implications for susceptible populations', *Annals of the American Thoracic Society*, 15 (Suppl. 2) S64–S68, doi:10.1513/AnnalsATS.201707-574MG.

Hooper P, Foster S, Edwards N, Turrell G, Burton N, Giles-Corti B and Brown WJ (2020) 'Positive HABITATS for physical activity: examining use of parks and its contribution to physical activity levels in mid-to older-aged adults', *Health & Place*, 63:102308, doi:10.1016/j.healthplace.2020.102308.

Horlings E, Schenau S, Hein L, Lof M, de Jongh L and Polder M (2020) *Experimental monetary valuation of ecosystem services and assets in the Netherlands*, Wageningen University and Research, The Hague, Netherlands, https://seea.un.org/content/experimental-monetary-valuation-ecosystem-services-and-assets-netherlands.

Hu Z, Liebens J and Rao KR (2008) 'Linking stroke mortality with air pollution, income, and greenness in northwest Florida: an ecological geographical study', *International Journal of Health Geography* 7:20, https://doi.org/10.1186/1476-072X-7-20.

Hua L, Zhang X, Nie Q, Sun F and Tang L (2020) 'The impacts of the expansion of urban impervious surfaces on urban heat islands in a coastal city in China', *Sustainability*, 12(2):475–496, doi:10.3390/su12020475.

Hussain RI, Walcher R, Eder R, Allex B, Wallner P, Hutter H-P et al. (2019) 'Management of mountainous meadows associated with biodiversity attributes, perceived health benefits and cultural ecosystem services', *Nature Research: Scientific Reports* 9:14977, doi:10.1038/s41598-019-51571-5.

Ideno Y, Hayashi K, Abe Y, Ueda K, Iso H, Noda M et al. (2017) 'Blood pressure-lowering effect of *Shinrin-yoku* (forest bathing): a systematic review and meta-analysis' *BMC Complementary and Alternative Medicine*, 17:409, doi:10.1186/s12906-017-1912-z.

James P, Hart JE, Banay RF and Laden F (2016) 'Exposure to greenness and mortality in a nationwide prospective cohort study of women', *Environmental Health Perspectives* 124(9):1344–1352, doi:10.1289/ehp.1510363.

Jang J, Lee W, Choi M, Kang C and Kim H (2020) 'Roles of urban heat anomaly and land-use/land-cover on the heat-related mortality in the national capital region of South Korea: a multi-districts time-series study', *Environment International*, 145:106127, doi:10.1016/j.envint.2020.106127.

Janhäll S (2015) 'Review on urban vegetation and particle air pollution – deposition and dispersion', *Atmospheric Environment*, 105:130–137, doi:10.1016/j.atmosenv.2015.01.052.

Jenerette G, Harlan S, Stefanov W and Martin C (2011) 'Ecosystem services and urban heat riskscape moderation: water, green spaces, and social inequality in Phoenix, USA', *Ecological Applications*, 21(7):2637–2651, doi:10.1890/10-1493.1.

Jennings V and Gaither C (2015) 'Approaching environmental health disparities and green spaces: an ecosystem services perspective', *International Journal of Environmental Research and Public Health*, 12(2):1952–1968, doi:10.3390/ijerph120201952.

Jimenez MP, DeVille N, Eilliot EG, Schiff JE, Wilt GE, Hart JE and James P (2021) 'Associations between nature exposure and health: a review of the evidence', *International Journal of Environmental Research and Public Health*, 18(9):4790, doi:10.3390/ijerph18094790.

Jones L, Vieno M, Morton D, Cryle P, Holland M, Carnell E et al. (2017) *Developing estimates for the valuation of air pollution removal in Ecosystem accounts*, Centre for Ecology and Hydrology, London, United Kingdom, https://seea.un.org/content/developing-estimates-valuation-air-pollution-removal-ecosystem-accounts.

Joung D, Lee B, Lee J, Lee C, Koo S, Park C et al. (2020) 'Measures to promote rural healthcare tourism with a scientific evidence-based approach', *International Journal of Environmental Research and Public Health* 17(9):3266, doi:10.3390/ijerph17093266.

Kabisch N, van den Bosch M and Lafortezza R (2017) 'The health benefits of nature-based solutions to urbanization challenges for children and the elderly – a systematic review', *Environmental Research*, 159:362–373. doi:10.1016/j.envres.2017.08.004.

Kalkstein LS, Sailor DJ, Shickman K, Sheridan S and Vanos J (2013) *Assessing the health impacts of urban heat island reduction strategies in the district of Columbia*, Global Cool Cities Alliance, Washington DC.

Kellert SR and Wilson EO (eds) (1993) *The biophilia hypothesis*, Island Press, Washington, DC.

Kilbourne EM, Choi K, Jones TS and Thacker SB (1982) 'Risk factors for heatstroke: a case-control study', *The Journal of the American Medical Association* 247(24):3332–3336, doi:10.1001/jama.1982.03320490030031.

Kim EJ and Kim H (2017) 'Effect modification of individual- and regional-scale characteristics on heat wave-related mortality rates between 2009 and 2012 in Seoul, South Korea', *Science of the Total Environment*, 595:141–148, doi:10.1016/j.scitotenv.2017.03.248.

Knowlton K, Rotkin-Ellman M, Geballe L, Max W and Solomon GM (2011) 'Six climate change related events in the United States accounted for about $14 billion in lost lives and health costs', *Health Affairs*, 30(11), doi:10.1377/htlhaff.2011.0229.

Kobayashi H, Ikei H, Song C, Kahawa T and Miyazaki Y (2021) 'Comparing the impact of forest walking and forest viewing on psychological states', *Urban Forestry and Urban Greening*, 57:126920, doi:10.1016/j.ufug.2020.126920.

Kolokotsma D, Lilli A, Lilli M and Nikolaidis N (2020) 'On the impact of nature-based solutions on citizens' health and wellbeing', *Energy and Buildings* 229:110527, doi:10.1016/j.enbuild.2020.110527.

Kosanic A and Petzold J (2020) 'A systematic review of cultural ecosystem services and human wellbeing', *Ecosystem Services* 45(C):101168, doi:10.1016/j.ecoser.2020.101168.

Kua K and Lee S (2021) 'The influence of residential greenness on mortality in the Asia-Pacific region: a systematic review and meta-analysis', *Perspectives in Public Health*, doi:10.1177/17579139211011496.

Kumar P, Druckman A, Gallagher J, Gatersleben B, Allison S, Eisenman TS et al. (2019) 'The nexus between air pollution, green infrastructure and human health', *Environment International*, 133(Part A):105181, doi:10.1016/j.envint.2019.105181.

Kumar R, Singh MC, Singh MC, Ahlawat SK, Thakur JS, Srivastava A et al. (2006) 'Urbanization and coronary heart disease: a study of urban-rural differences in northern India', *Indian Heart Journal*, 58(2):126–30.

Kummu M, de Moel H, Ward PJ and Varis O (2011) 'How close do we live to water? A global analysis of population distance to freshwater bodies', *PLoS One*, 6(6):e20578, doi:10.1371/journal.pone.0020578.

Kuo M (2015) 'How might contact with nature promote human health? Promising mechanisms and a possible central pathway', *Frontiers in Psychology*, 6:1093, doi:10.3389/fpsyg.2015.01093.

Lachowycz K and Jones A (2011) 'Green space and obesity: a systematic review of the evidence', *Obesity Reviews*, 12:e183–e189, doi:10.1111/j.1467-789X.2010.00827.x.

—— (2013) 'Towards a better understanding of the relationship between greenspace and health: development of a theoretical framework', *Landscape and Urban Planning*, *118*, 62–69, doi:10.1016/j.landurbplan.2012.10.012.

Laothawornkitkul J, Taylor JE, Paul ND and Hewitt CN (2009) 'Biogenic volatile organic compounds in the Earth system', *New Phytologist*, 183(1):27–51, doi:10.1111/j.1469-8137.2009.02859.x.

Laurent O, Benmarhnia T, Milesi C, Hu J, Kleeman MJ, Cockburn M and Wu J (2019) 'Relationships between greenness and low birth weight: investigating the interaction and mediation effects of air pollution', *Environmental Research*, 175:124–132, doi:10.1016/j.envres.2019.05.002.

Lee PC, Wu CD, Tsai HJ, Lin S, Wu CK, Hung CY and Yao TC (2021) 'Residential greenness and birth outcomes: evaluating the mediation and interaction effects of particulate air pollution', *Ecotoxicology and Environmental Safety*, 211:111915, doi:10.1016/j.ecoenv.2021.111915.

Liao J, Chen X, Xu S, Li Y, Zhang B, Cao Z et al. (2019) 'Effect of residential exposure to green space on maternal blood glucose levels, impaired glucose tolerance, and gestational diabetes mellitus', *Environmental Research* 176:108526, doi:10.1016/j.envres.2019.108526.

Liu GC, Wilson JS, Qi R and Ying J (2007), 'Green neighborhoods, food retail and childhood overweight: differences by population density', *American Journal of Health Promotion*, 21(4_suppl):317–25, doi:10.4278%2F0890-1171-21.4s.317.

Longden T (2018) 'Measuring temperature-related mortality using endogenously determined thresholds', *Climatic Change*, 150:343–375, doi:10.1007/s10584-018-2269-0.

Longden T, Quilty S, Haywood P, Hunter A and Gruen R (2020) 'Heat-related mortality: an urgent need to recognise and record', *Lancet Planet Health*, 4(5):171, doi:10.1016/S2542-5196(20)30100-5.

Loureiro A and Veloso S (2017) 'Green exercise, health and well-being', in Fleury-Bahi G, Pol E and Navarro O (eds) *Handbook of environmental psychology and quality of life research*, Springer International, Switzerland, doi:10.1007/978-3-319-31416-7_8.

Lovasi GS, O'Neil-Dunne JP, Lu JW, Sheehan D, Perzanowski MS, MacFaden SW et al. (2013a) 'Urban tree canopy and asthma, wheeze, rhinitis, and allergic sensitization to tree pollen in a New York City birth cohort', *Environmental health perspectives*, 121(4):494, doi:10.1289/ehp.1205513.

Lovasi GS, Schwartz-Soicher O, Quinn JW, Berger DK, Neckerman KM, Jaslow R et al. (2013b), 'Neighborhood safety and green space as predictors of obesity among preschool children from low-income families in New York City', *Preventive Medicine*, 57(3):189–93, doi:10.1016/j.ypmed.2013.05.012.

Lovibond SH and Lovibond PF (1995) *Manual for the depression anxiety and stress scales*, (2nd edn), Psychology Foundation, Sydney, http://trove.nla.gov.au/work/30421447.

Ma W, Chen R and Kan H (2014) 'Temperature-related mortality in 17 large Chinese cities: how heat and cold affect mortality in China', *Environmental Research*, 34:127–33, doi:10.1016/j.envres.2014.07.007.

Maas J, van Dillen ME, Verheij RA and Groenewegen PP (2009) 'Social contacts as a possible mechanism behind the relation between green space and health', *Health & Place*, 15:586–95, doi:10.1016/j.healthplace.2008.09.006.

Mackay GJ and Neill JT (2010) 'The effect of "green exercise" on state anxiety and the role of exercise duration, intensity, and greenness: a quasi-experimental study', *Psychology of Sport and Exercise*, 11(3):238–45, doi:10.1016/j.psychsport.2010.01.002.

Madrigano J, Mittleman M, Baccarelli A, Goldberg R, Melly S, von Klot S and Schwartz J (2013) 'Temperature, myocardial infarction, and mortality: effect modification by individual and area-level characteristics', *Epidemiology*, 24(3):439–446. doi:10.1097/EDE.0b013e3182878397.

Marando F, Salvatori E, Sebastiani A, Fusaro L and Manes F (2019) 'Regulating ecosystem services and green infrastructure: assessment of urban heat island effect mitigation in the municipality of Rome, Italy', *Ecological Modelling* 392:92–102, https://doi.org/10.1016/j.ecolmodel.2018.11.011.

Marselle MR, Bowler DE, Watzema J, Eichenberg D, Kirsten T and Bonn A (2020) 'Urban street tree biodiversity and antidepressant prescriptions', *Nature: Scientific Reports* 10:22445, doi:10.1038/s41598-020-79924-5.

McEachan RR, Prady SL, Smith G, Fairley L, Cabieses B, Gidlow C et al. (2016) 'The association between green space and depressive symptoms in pregnant women: moderating roles of socioeconomic status and physical activity', *Journal of Epidemiology and Community Health*, 70(3):253–259, doi:10.1136/jech-2015-205954.

McHorney CA, Ware JE and Raczek AE (1993) 'The MOS 36-Item Short-Form Health Survey (SF-36): II. Psychometric and Clinical Tests of Validity in Measuring Physical and Mental Health Constructs', *Medical Care*, 31(3):247–263, doi:10.1097/00005650-199303000-00006.

Mekala GD, Jones RN and MacDonald DH (2015) ‘Valuing the benefits of creek rehabilitation: building a business case for public investments in urban green infrastructure’, *Environmental Management*, 55:1354–1365, doi:10.1007/s00267-015-0471-7.

Milcu AJ, Hanspach J, Abson D and Fischer J (2013) ‘Cultural ecosystem services: a literature review and prospects for future research’, *Ecology and Society*, 18(3):44–79, doi:10.5751/ES-05790-180344.

Mirzaei PA (2015) ‘Recent challenges in modelling of Urban Heat Island’, *Sustainable Cities and Society*, 76, doi:10.1016/j.scs.2015.04.001.

Morais L, Lopes A and Nogueira P (2021) ‘Human health outcomes at the neighbourhood scale implications: elderly’s heat-related cardiorespiratory mortality and its influencing factors’, *Science of the Total Environment*, 760:144036, doi:10.1016/j.scitotenv.2020.144036.

Moseley D, Connolly T, Sing L and Watts K (2018) ‘Developing an indicator for the physical health benefits of recreation in woodlands’, *Ecosystem Services*, 21:420–432, doi:10.1016/j.ecoser.2017.12.008.

Mowafi M, Khadr Z, Bennett G, Hill A, Kawachi I and Subramanian SV (2012) ‘Is access to neighborhood green space associated with BMI among Egyptians? A multilevel study of Cairo neighborhoods’, *Health & Place*, 18(2):385–390, doi:10.1016/j.healthplace.2011.12.002.

Mueller N, Rojas-Rueda D, Basagaña X, Cirach M, Cole-Hunter T, Dadvand P et al. (2017) ‘Urban and transport planning related exposures and mortality: a health impact assessment for cities’, *Environmental Health Perspectives*, 125(1):89–96, doi:10.1289/EHP220.

Murage P, Kovats S, Sarran C, Taylor J, McInnes R and Hajat S (2020) ‘What individual and neighbourhood-level factors increase the risk of heat-related mortality? A case-crossover study of over 185,000 deaths in London using high-resolution climate datasets’, *Environment International*, 134:105292, doi:10.1016/j.envint.2019.105292.

Newbury JB, Stewart R, Fisher HL, Beevers S, Dajnak D, Broadbent M et al. (2021) ‘Association between air pollution exposure and mental health service use among individuals with first presentations of psychotic and mood disorders: retrospective cohort study’, *The British Journal of Psychiatry*, 219(6):678–685, doi:10.1192/bjp.2021.119.

NICE (National Institute of Health and Care Excellence) (2013) *Judging whether public health interventions offer value for money*, [local government briefing (LGP 10)], https://www.nice.org.uk/advice/lgb10/chapter/judging-the-costeffectiveness-of-public-health-activities.

Nie Z, Yang B, Ou Y, Bloom MS, Han F, Qu Y et al. (2020) ‘Maternal residential greenness and congenital heart defects in infants: a large case-control study in southern China’, *Environment International*,142:105859, doi:10.1016/j.envint.2020.105859.

Nowak DJ, Crane DE and Stevens JC (2006) ‘Air pollution removal by urban trees and shrubs in the United States’, *Urban Forestry and Urban Greening*, 4:115–123, doi:10.1016/j.ufug.2006.01.007.

Nowak DJ, Hirabayashi S, Bodine A and Greenfield E (2014) ‘Tree and forest effects on air quality and human health in the United States’, *Environmental Pollution*, 193:199–229, doi:10.1016/j.envpol.2014.05.028.

Nowak DJ, Hirabayashi S, Bodine A and Hoehn R (2013) ‘Modeled PM2.5 removal by trees in ten US cities and associated health effects’, *Environmental Pollution*, 178:395–402, doi:10.1016/j.envpol.2013.03.050.

Nowak DJ, Hirabayashi S, Doyle M, McGovern M and Pasher J (2018) 'Air pollution removal by urban forests in Canada and its effect on air quality and human health', *Urban Forestry and Urban Greening*, 29:40–48, doi:10.1016/j.ufug.2017.10.019.

Nowak DJ, Rowntree RA, McPherson EG, Sisinni SM, Kerkmann ER and Stevens JC (1996) 'Measuring and analyzing urban tree cover', *Landscape and Urban Planning*, 36(1):49–57, doi:10.1016/S0169-2046(96)00324-6.

Nyelele C, Kroll C and Nowak D (2019) 'Present and future ecosystem services of trees in the Bronx, NY', *Urban Forestry and Urban Greening*, 42:10–20, doi:10.1016/j.ufug.2019.04.018.

O'Brien L and Forster J (2021) 'Physical activity supporting connection to nature, and helping to maintain wellbeing during the COVID-19 restrictions in England', *International Journal of Environmental Research and Public Health*, 18(9):4585, doi:10.3390/ijerph18094585.

OECD (Organisation for Economic Co-operation and Development) (2021) *Measuring well-being and progress: well-being research*, OECD, Paris, accessed 23 Jun 2022, https://www.oecd.org/wise/measuring-well-being-and-progress.htm.

Pascal M, Goria S, Wagner V, Sabastia M, Guillet A, Cordeau E et al. (2021) 'Greening is a promising but likely insufficient adaptation strategy to limit the health impacts of extreme heat', *Environment International*, 151:106441, doi:10.1016/j.envint.2021.106441.

Paths for All (2013) Glasgow health walks, social return on investment analysis, [summary report], Paths for All, Edinburgh, Scotland, https://www.pathsforall.org.uk/resource/sroi-report-glasgow-health-walks.

Paton-Walsh C, Rayner P, Simmons J, Fiddes SL, Schofield R, Bridgman H et al. (2019) 'A clean air plan for Sydney: an overview of the special issue on air quality in New South Wales', *Atmosphere*, 10(12):774–811, doi:10.3390/atmos10120774.

Paulin MJ, Remme RP, van der Hoek DCJ, de Knegt B, Koopman KR, Breure AM et al. (2020) 'Towards nationally harmonized mapping and quantification of ecosystem services', *Science of the Total Environment*, 703:134973, doi:10.1016/j.scitotenv.2019.134973.

Pedersen M, Stayner L, Slama R, Sørensen M, Figueras F, Nieuwenhuijsen MJ et al. (2014) 'Ambient air pollution and pregnancy-induced hypertensive disorders: a systematic review and meta-analysis', *Hypertension*, 64(3):494–500, doi:10.1161/HYPERTENSIONAHA.114.03545.

Pereira G, Christian H, Foster S, Boruff BJ, Bull F, Knuiman M and Giles-Corti B (2013) 'The association between neighborhood greenness and weight status: an observational study in Perth Western Australia', *Environmental Health*,12:49, doi:10.1186/1476-069X-12-49.

Pereira G, Foster S, Martin K, Christian H, Boruff BJ, Knuiman M and Giles-Corti B (2012) 'The association between neighborhood greenness and cardiovascular disease: an observational study', *BMC Public Health* 12:466, http://www.biomedcentral.com/1471-2458/12/466.

Pope A and Dockery DW (2006) 'Health effects of fine particulate air pollution: lines that connect', *Journal of the Air & Waste Management Association* 56(6):709–742, doi:10.1080/10473289.2006.10464485.

Powe NA and Willis KG (2004) 'Mortality and morbidity benefits of air pollution (SO_2 and PM10) absorption attributable to woodland in Britain', *Journal of Environmental Management*, 70(2):119–28, doi:10.1016/j.jenvman.2003.11.003.

Prady SL, Miles JN, Pickett KE, Fairley L, Bloor K, Gilbody S et al. (2013) 'The psychometric properties of the subscales of the GHQ-28 in a multi-ethnic maternal sample: results from the Born in Bradford cohort', *BMC Psychiatry*, 13:55, doi:10.1186/1471-244X-13-55.

Preiss P, Friedrich R and Klotz V (2008) *Report on the procedure and data to generate averaged/aggregated data*, NEEDS Project, Stuttgart, Germany.

Pretty J, Peacock J, Hine R, Sellens M, South N and Griffin M (2007) 'Green exercise in the UK countryside: effects on health and psychological well-being, and implications for policy and planning', *Journal of Environmental Planning and Management*, 50(2):211–31, doi:10.1080/09640560601156466.

Pröbstl-Haider U (2015) 'Cultural ecosystem services and their effects on human health and well-being: a cross-disciplinary methodological review', *Journal of Outdoor Recreation and Tourism*, 10:1–13, doi:10.1016/j.jort.2015.07.004.

Prüss-Ustün A, Wolf J, Corvalán C, Neville T, Bos R and Neira M (2017) 'Diseases due to unhealthy environments: an updated estimate of the global burden of disease attributable to environmental determinants of health', *Journal of Public Health* 39(3):464–75, doi:10.1093/pubmed/fdw085.

Qiu C, Ji J and Bell M (2021) 'Effect modification of greenness on temperature-mortality relationship among older adults: a case-crossover study in China', *Environmental Research*, 197, doi:10.1016/j.envres.2021.111112.

Remme RP, Edens B, Schröter M and Hein L (2015) 'Monetary accounting of ecosystem services: a test case for Limburg province, the Netherlands', *Ecological Economics* 112: 116–128, doi:10.1016/j.ecolecon.2015.02.015.

Richardson EA and Mitchell R (2010), 'Gender differences in relationships between urban green space and health in the United Kingdom', *Social Science and Medicine*, 71(3): 568–575, doi:10.1016/j.socscimed.2010.04.015.

Richardson EA, Mitchell R, Hartig T, de Vries S, Astell-Burt T and Frumkin H (2012) 'Green cities and health: a question of scale?', *Journal of Epidemiology and Community Health*, 66(2):160–165, https://doi.org/10.1136/jech.2011.137240.

Richardson EA, Pearce J, Mitchell R and Kingham S (2013) 'Role of physical activity in the relationship between urban green space and health', *Public Health*, 127:318–324, doi:10.1016/j.puhe.2013.01.004.

Rijnhart JJ, Lamp SJ, Valente MJ, MacKinnon DP, Twisk JW and Heymans MW (2021) 'Mediation analysis methods used in observational research: a scoping review and recommendations', *BMC Medical Research Methodology*, 21(1):1–7, doi:10.1186/s12874-021-01426-3.

RIVM (2012) *Maatschappelijke kosten voor astma, COPD en respiratoire allergie [Societal costs of asthma, COPD and respiratory allergy in the Netherlands]*, RIVM – National Institute for Public Health and the Environment, Bilthoven, the Netherlands.

Rojas-Rueda D, Nieuwenhuijsen MJ, Gascon M, Perez-Leon and Mudu P (2019) 'Green spaces and mortality: a systematic review and meta-analysis of cohort studies', *The Lancet Planetary Health*, 3(11):e469-e477, doi:10.1016/S2542-5196(19)30215-3.

Rosenthal J, Kinney P and Metzger K (2014) 'Intra-urban vulnerability to heat-related mortality in New York City, 1997–2006', *Health & Place*, 30:45–60, doi:10.1016/j.healthplace.2014.07.014.

Salmond JA, Tadaki M, Vardoulakis S, Arbuthnott K, Coutts A, Demuzere M et al. (2016) ‘Health and climate related ecosystem services provided by street trees in the urban environment’, *Environmental Health*, 15(S36), doi:10.1186/s12940-016-0103-6.

Sandifer PA, Sutton-Grier AE and Ward BP (2015) ‘Exploring connections among nature, biodiversity, ecosystem services, human health and well-being: opportunities to enhance health and biodiversity conservation’, *Ecosystem Services*, 12:1–15, doi:10.1016/j.ecoser.2014.12.007.

Sangha KK and Russell-Smith J (2017) ‘Towards an indigenous ecosystem services valuation framework: a north Australian example’, *Conservation and Society*, 15(3):255–269, doi:10.1016/j.ecoser.2018.03.017.

Sanghar KK, Preece L, Villarreal-Rosas J, Kegamba JJ, Paudyal K, Warmenhoven T and Ramakrishnan PS (2018) ‘An ecosystem services framework to evaluate indigenous and local peoples’ connections with nature’, *Ecosystem Services*, 31:111–125, doi:10.1016/j.ecoser.2018.03.017.

Sanghar KK, Russell-Smith J and Costanza R (2019), ‘Mainstreaming indigenous and local communities’ connections with nature for policy decision-making’, *Global Ecology and Conservation*, 19:e00668, doi:10.1016/j.gecco.2019.e00668.

Saunders A, Duncan J, Hurley J, Amati M, Caccetta P, Chia J and Boruff B (2020) ‘Leaf my neighbourhood alone! Predicting the influence of densification on residential tree canopy cover in Perth’, *Landscape and Urban Planning*, 199:103804, doi:10.1016/j.landurbplan.2020.103804.

Schinasi LH, Bloch JR, Melly S, Zhao Y, Moore K and De Roos AJ (2020) ‘High ambient temperature and infant mortality in Philadelphia, Pennsylvania: a case-crossover study’, *American Journal of Public Health*, 110(2):189–195, doi:10.2105/AJPH.2019.305442.

Schraufnagel DE, Balmes JR, Cowl CT, De Matteis S, Jung S-H, Mortimer K et al. (2019) ‘Air pollution and non-communicable diseases: a review by the forum of International Respiratory Societies’ Environmental Committee – Part 1: the damaging effects of air pollution’, *Chest*, 155(2):409–416, doi:10.1016/j.chest.2018.10.042.

SEEA (System of Environmental Economic Accounting) (2022) *System of Environmental Economic Accounting*, SEEA website, United Nations, accessed 14 February 2022, https://seea.un.org/.

Seo S, Choi S, Kim K, Min Kim S and Park SM (2019) ‘Association between urban green space and the risk of cardiovascular disease: a longitudinal study in seven Korean metropolitan areas’, *Environment International*, 125:51–57, doi:10.1016/j.envint.2019.01.038.

Sera F, Armstrong B, Tobias A, Vicedo-Cabrera AM, Åström C, Bell ML, Chen BY et al. (2019) ‘How urban characteristics affect vulnerability to heat and cold: a multi-country analysis’, *International Journal of Epidemiology*, 48(4):1101–1112, doi:10.1093/ije/dyz008.

Shahmohamadi P, Che-Ani A, Etessam I, Maulud K and Tawil N (2011) ‘Healthy environment: the need to mitigate urban heat island effects on human health’, *Procedia Engineering*, 20:61–70, doi:10.1016/j.proeng.2011.11.139.

Shanahan DF, Bush R, Gaston KJ, Lin BB, Dean J, Barber E and Fuller RA (2016) ‘Health benefits from nature experiences depend on dose’, *Nature: Scientific Reports*, 6:28551, doi:10.1038/srep28551.

Shen Y and Lung S (2016) ‘Can green structure reduce the mortality of cardiovascular diseases?’, *Science of the Total Environment*, 566–567:1159–1167, doi:10.1016/j.scitotenv.2016.05.159.

Sinha P, Coville R, Hirabayashi S, Lim B, Endreny T and Nowak D (2021) 'Modeling lives saved from extreme heat by urban tree cover', *Ecological Modelling*, 449:109553, doi:10.1016/j.ecolmodel.2021.109553.

Smith M and Ram Y (2016) 'Tourism, landscapes and cultural ecosystem services: a new research tool', *Tourism Recreation Research*, 42:113–119, doi:10.1080/02508281.2016.1253206.

Smith N, Georgiou M, King AC, Tieges Z, Webb S and Chastin S (2021) 'Urban blue spaces and human health: a systematic review and meta-analysis of quantitative studies' *Cities*, 119: 103413, doi:10.1016/j.cities.2021.103413.

Smith T, Bulkan J, Zerriffi H and Tansey J (2019) 'Indigenous peoples, local communities and payments for ecosystem services', *Canadian Geographer*, 63(4):616–630, doi:10.1111/cag.12553.

Sobngwi E, Mbanya J, Unwin NC, Porcher R, Kengne A, Fezeu L et al. (2004) 'Exposure over the life course to an urban environment and its relation with obesity, diabetes, and hypertension in rural and urban Cameroon', *International Journal of Epidemiology*, 33(4):769–776, doi:10.1093/ije/dyh044.

Solecki WD, Rosenzweig C, Parshall L, Pope G, Clark M, Cox J and Wiencke M (2005) 'Mitigation of the health island effect in urban New Jersey', *Global Environmental Change – Part B: Environmental Hazards*, 6:30–49, doi:10.1016/j.hazards.2004.12.002.

Son J, Lane K, Lee J and Bell M (2016) 'Urban vegetation and heat-related mortality in Seoul, Korea', *Environmental Research*, 151:728–733, doi:10.1016/j.envres.2016.09.001.

Song C, Ikei H and Miyazaki Y (2016) 'Physiological effects of nature therapy: a review of the research in Japan', *International Journal of Environmental Research and Public Health*, 13:781, doi:10.3390/ijerph13080781.

Song C, Joung D, Ikei H, Igarashi M, Aga M, Burn-Jin P et al. (2013) 'Physiological and psychological effects of walking on young males in urban parks in winter', *Journal of Physiological Anthropology*, 32(1):18–23, doi:10.1186/1880-6805-32-18.

Spronken-Smith RA, Oke TR and Lowry WP (2000) 'Advection and the surface energy balance across an irrigated urban park', *International Journal of Climatology*, 20:1033–1047, doi:10.1002/1097-0088(200007)20:9%3C1033::AID-JOC508%3E3.0.CO;2-U.

Stoeckl N, Jarvis D, Larson S, Larson A, Grainger D and Ewamian Aboriginal Corporation (2021) 'Australian Indigenous insights into ecosystem services: beyond services towards connectedness – people, place and time' *Ecosystem Services*, 50:101341, doi:10.1016/j.ecoser.2021.101341.

Stone B, Vargo J, Liu P, Habeeb D, DeLucia A, Trail M et al. (2014) 'Avoided heat-related mortality through climate adaptation strategies in three US cities', *PLoS One*, 9(6):e100852, doi:10.1371/journal.pone.0100852.

Sugiyama T, Leslie E, Giles-Corti B and Owen N (2008) 'Associations of neighbourhood greenness with physical and mental health: do walking, social coherence and local social interaction explain the relationships?', *Journal of Epidemiology and Community Health* 62(5):e9, doi:10.1136/jech.2007.064287.

Sun Y, Sheridan P, Laurent O, Li J, Sacks DA, Fischer H et al. (2020) 'Associations between green space and preterm birth: windows of susceptibility and interaction with air pollution', *Environment International*, 142:105804, doi:10.1016/j.envint.2020.105804.

Tan X, Hirabayashi S and Shibata S (2021) 'Estimation of ecosystem services provided by street trees in Kyoto, Japan', *Forests*, 12:311–332, doi:10.3390/f12030311.

Tapsuwan S, Marcos-Martinez R, Schandl H and Yu Z (2021) 'Valuing ecosystem services of urban forests and open spaces: application of the SEEA framework in Australia', *Agricultural and Resource Economics* 65(1):37–65, https://doi.org/10.1111/1467-8489.12416.

Taylor L and Hochuli DF (2017) 'Defining green space: multiple uses across multiple disciplines', *Landscapes and Urban Planning*, 158:25–38, https://doi.org/10.1016/j.landurbplan.2016.09.024.

Tennant R, Hiller L, Fishwick R, Platt S, Joseph S, Weich S et al. (2007) 'The Warwick-Edinburgh Mental Well-being Scale (WEMWBS): development and UK validation', *Health and Quality of Life Outcome*s 5(63), https://hqlo.biomedcentral.com/articles/10.1186/1477-7525-5-63.

Thompson Coon J, Boddy K, Stein K et al. (2011) 'Does participating in physical activity in outdoor natural environments have a greater effect on physical and mental wellbeing than physical activity indoors? A systematic review', *Environmental Science and Technology* 45(5):1761–1772, doi:10.1021/es102947t.

Tsunetsugu Y, Park B-J and Miyazaki Y (2010) 'Trends in research related to 'Shinrin-yoku' (taking in the forest atmosphere or forest bathing) in Japan', *Environmental Health and Preventive Medicine*, 15(27):27–37, doi:10.1007/s12199-009-0091-z.

Twohig-Bennett C and Jones A (2018) 'The health benefits of the great outdoors: a systematic review and meta-analysis of greenspace exposure and health outcomes', *Environmental Research*, 166:628–637, doi:10.1016/j.envres.2018.06.030.

Tyrväinen L, Ojala A, Korpela K, Lanki T, Tsunetsugu Y and Kagawa T (2014) 'The influence of urban green environments on stress relief measures: a field experiment', *Journal of Environmental Psychology*, 38:1–9.

Uejio C, Wilhelmi O, Golden J, Mills D, Gulino S and Samenow J (2011) 'Intra-urban societal vulnerability to extreme heat: the role of heat exposure and the built environment, socioeconomics, and neighbourhood stability', *Health & Place* 17(2):498–507, doi:10.1016/j.healthplace.2010.12.005.

United Nations (2014) System of Environmental-Economic Accounting 2012: Experimental Ecosystem Accounting, United Nations, New York, accessed 7 July 2022, https://openknowledge.worldbank.org/handle/10986/23959.

United Nations, Department of Economic and Social Affairs, Population Division (2019) *World Urbanization Prospects: the 2018 Revision* (ST/ESA/SER.A/420). New York: United Nations.

United Nations, European Commission, International Monetary Fund, OECD, World Bank (2009) *System of National Accounts 2008,* United Nations, New York, accessed 7 July 2022, https://unstats.un.org/unsd/nationalaccount/sna2008.asp.

United Nations et al. (2021) System of Environmental-Economic Accounting – Ecosystem Accounting (SEEA EA), [white cover publication, pre-edited text subject to official editing], United Nations, New York, accessed 7 July 2022, https://seea.un.org/ecosystem-accounting.

United Nations General Assembly (2015) *Transforming our world: the 2030 Agenda for Sustainable Development*, A/RES/70/1, United Nations General Assembly, accessed 29 June 2022, https://www.un.org/en/development/desa/population/migration /generalassembly/docs/globalcompact/A_RES_70_1_E.pdf.

US EPA (United States Environmental Protection Agency) (2022) *BenMAP 4.0 (January 2103 version)*, accessed 1 August 2022, https://www.epa.gov/benmap/benmap-40.

Vallecillo S, La Notte A, Polce C, Zulian G, Alexandris N, Ferrini S and Maes J (2018) *Ecosystem services accounting: Part I – Outdoor recreation and crop pollination*, [EUR 29024 EN], Publications Office of the European Union, Luxembourg, doi:10.2760/619793, JRC110321.

VanderWeele T (2015) *Explanation in causal inference: methods for mediation and interaction*, Oxford University Press, New York.

Vanos SSJ, Kalkstein L, Sailor D and Schickman K (n.d.) Assessing the health impacts of urban heat island reduction strategies in the cities of Baltimore, Los Angeles, and New York, accessed 1 August 2022, https://www.adaptationclearinghouse.org/resources/assessing-the-health-impacts-of-urban-heat-island-reduction-strategies-in-the-cities-of-baltimore-los-angeles-and-new-york.html.

Venter Z, Krog N and Barton D (2020) 'Linking green infrastructure to urban heat and human health risk mitigation in Oslo, Norway', *Science of the Total Environment*, 709:136193, doi:10.1016/j.scitotenv.2019.136193.

Ventriglio A, Bellomo A, di Gioia I, Di Sabatino D, Favale D, De Berardis D and Cianconi P (2021) 'Environmental pollution and mental health: a narrative review of literature', *CNS spectrums*, 26(1):51–61, doi:10.1017/S1092852920001303.

Vert C, Nieuwenhuijsen M, Gascon M, Grellier J, Fleming LE, White MP et al. (2019) 'Health benefits of physical activity related to an urban riverside regeneration', *International Journal of Environmental Research and Public Health*, 16(3):462, doi:10.3390/ijerph16030462.

Vieira J, Matos P, Mexia T, Silva P, Lopes N and Freitas C (2018) 'Green spaces are not all the same for the provision of air purification and climate regulation services: the case of urban parks', *Environmental Research*, 160:306–313, doi:10.1016/j.envres.2017.10.006.

Vienneau D, de Hoogh K, Faeh D, Kaufmann M, Wunderli JM, Röösli M and the SNC Study Group (2017) 'More than clean air and tranquillity: residential green is independently associated with decreasing mortality', *Environment International*, 108:176–184, doi:10.1016/j.envint.2017.08.012.

Volker S, Baumeister H, Classen T, Hornberg C and Kistemann T (2013) 'Evidence for the temperature-mitigating capacity of urban blue space – a health geographic perspective', *Erdkunde*, 67(4):355–371, doi:10.3112/erdkunde.2013.04.05.

Walters S, Griffiths RK and Ayres JG (1994) 'Temporal association between hospital admissions for asthma in Birmingham and ambient levels of sulphur dioxide and smoke', *Thorax*, 49(2):133–40, doi:10.1136/thx.49.2.133.

Wania A, Bruse M, Blond N and Weber C (2012) 'Analysing the influence of different street vegetation on traffic-induced particle dispersion using microscale simulations', *Journal of Environmental Management*, 94(1):91–101, doi:10.1016/j.jenvman.2011.06.036.

Ware JE, Kosinski M and Keller SD (1996) 'A 12-item Short-form Health Survey: construction of scales and preliminary tests of reliability and validity', *Medical Care* 34(3):220–33, doi:10.1097/00005650-199603000-00003.

Warren JL (1973) *Green space for air pollution control*, [technical report 50], School of Forest Resources, North Carolina State University, Raleigh, North Carolina.

Weber KA, Yang W, Lyons E, Stevenson DK, Padula AM and Shaw GM (2021) 'Green space, air pollution, neighbourhood factors, and preeclampsia in a population-based case-control study in California', *International Journal of Environmental Research and Public Health*, 18(10):5127, doi:10.3390/ijerph18105127.

Weier J and Herring D (2000) *Measuring vegetation (NDVI and EVI)*, NASA Earth Observatory: Washington, DC, United States.

White M, Elliott L, Gascon M, Roberts B and Fleming L (2020) 'Blue space, health and well-being: a narrative overview and synthesis of potential benefits', *Environmental Research*, 191:110169, doi:10.1016/j.envres.2020.110169.

White MP, Elliott LR, Taylor T, Wheeler BW, Spencer A, Bone A, Depledge MH and Fleming LE (2016) 'Recreational physical activity in natural environments and implications for health: a population based cross-sectional study in England', *Preventive Medicine*, 91:383–8, doi:10.1016/j.ypmed.2016.08.023.

Whiteoak K and Saiger J (2019) *Estimating the economic benefits of urban heat island mitigation – economic analysis*, Cooperative Research Centre for Water Sensitive Cities. Melbourne, Australia.

Whitmee S, Haines A, Beyrer C, Boltz F, Capon AG, de Souza Dias BF et al. (2015) 'Safeguarding human health in the Anthropocene epoch: report of The Rockefeller Foundation-Lancet Commission on planetary health', *Lancet* 386(10007):1973–2028. doi:10.1016/S0140-6736(15)60901-1 (erratum in: *Lancet* (2015) 386(10007):1944).

WHO (World Health Organization) (1946) *Preamble to the Constitution of the World Health Organization as adopted by the International Health Conference*, New York, 19–22 June 1946, WHO, New York.

—— (2014) *Health in all policies: Helsinki statement. Framework for country action*, WHO, accessed 17 March 2022, https://www.who.int/publications/i/item/9789241506908.

—— (6 October 2015) 'WHO calls for urgent action to protect health from climate change – sign the call', [news report], accessed 17 March 2022, https://www.who.int/news/item/06-10-2015-who-calls-for-urgent-action-to-protect-health-from-climate-change-sign-the-call.

—— (2018) *Air pollution and child health: prescribing clean air – summary report*, WHO, Geneva, accessed 24 June 2022, https://www.who.int/publications/i/item/air-pollution-and-child-health.

—— (2020) WHO Global Strategy on Health, Environment and Climate Change: the transformation needed to improve lives and wellbeing sustainably through healthy environments, WHO website, accessed 16 March 2022, https://www.who.int/publications/i/item/9789240000377.

—— (2021) *WHO global air quality guidelines: particulate matter (PM 2.5 and PM 10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide*, WHO, accessed 23 March 2022, https://apps.who.int/iris/handle/10665/345329.

Wolf KL, Lam ST, McKeen JK, Richardson GRA, van den Bosch M and Bardekijan AC (2020) 'Urban trees and human health: a scoping review', *International Journal of Environmental Research and Public Health*, 17(12):4371, doi:10.3390/ijerph17124371.

Wood L, Hooper P, Foster S and Bull F (2017) 'Public green spaces and positive mental health – investigating the relationship between access, quantity and types of parks and mental wellbeing', *Health & Place*, 48:63–71, doi:10.1016/j.healthplace.2017.09.002.

Wu H, Ye LP, Shi WZ and Clarke KC (2014) ‘Assessing the effects of land use spatial structure on urban heat islands using HJ–1B remote sensing imagery in Wuhan, China’, *International Journal of Applied Earth Observation and Geoinformation*, 32(1):67–78, doi:10.1016/j.jag.2014.03.019.

Xu Y, Dadvand P, Barrera-Gómez J, Sartini C, Marí-Dell’Olmo M, Borrell C et al. (2013) ‘Differences on the effect of heat waves on mortality by sociodemographic and urban landscape characteristics’, *Journal of Epidemiological Community Health*, 67(6):519–25, doi:10.1136/jech-2012-201899.

Xu Z, Tong S, Cheng J, Crooks JL, Xiang H, Li X et al. (2019a) ‘Heatwaves and diabetes in Brisbane, Australia: a population-based retrospective cohort study’, *International Journal of Epidemiology*, 48(4):1091–1100, doi:10.1093/ije/dyz048.

Xu Z, Tong S, Cheng J, Zhang Y, Wang N, Zhang Y et al. (2019b) ‘Heatwaves, hospitalizations for Alzheimer’s disease, and post-discharge deaths: a population-based cohort study’, *Environmental Research*, 178:108714, doi:10.1016/j.envres.2019.108714.

Yang BY, Markevych I, Bloom MS, Heinrich J, Guo Y, Morawska L et al. (2019) ‘Community greenness, blood pressure, and hypertension in urban dwellers: the 33 Communities Chinese Health Study’, *Environment International*, 123(2019):727–734, doi:10.1016/j.envint.2019.02.068.

Yang BY, Zhao T, Hu LX, Browning MHEM, Heinrich J, Dharmage SC et al. (2021) ‘Greenspace and human health: an umbrella review’, *The Innovation*, 2(4), doi:10.1016/j.xinn.2021.100164.

Zanobetti A, O’Neill MS, Gronlund CJ and Schwartz JD (2013) ‘Susceptibility to mortality in weather extremes: effect modification by personal and small area characteristics in a multi-city case-only analyses’, *Epidemiology*, 24(6):809–819, doi:10.1097/01.ede.0000434432.06765.91.

Zhang H, Liu L, Zeng Y, Liu M, Bi J and Ji JS (2021) ‘Effect of heatwaves and greenness on mortality among Chinese older adults’, *Environmental Pollution*, 290:118009, doi:10.1016/j.envpol.2021.118009.

Zhang L, Zhou S, Kwan M-P, Chen F and Lin R (2018) ‘Impacts of individual daily green space exposure on health based individual activity space and structural equation modelling’, *International Journal of Environmental Research and Public Health*, 15(10):2323, doi:10.3390/ijerph15102323.

Zhao Q, Guo Y, Ye T, Gasparrini A, Tong S, Overcenco A et al. (2021) ‘Global, regional, and national burden of mortality associated with non-optimal ambient temperatures from 2000 to 2019: a three-stage modelling study’, *Lancet Planetary Health*, 5(7):e415-e425, doi:10.1016/S2542-5196(21)00081-4.

Zhen WM, Shan ZH, Gong WS, Yan TA and Zheng SK (2013) ‘The weather temperature and air pollution interaction and its effect on hospital admissions due to respiratory system diseases in western China’, *Biomedical and Environmental Sciences*, 26:403–407, doi:10.3967/0895-3988.2013.05.011.

List of figures

List of tables

List of boxes

Related publications

The following AIHW reports might be of interest:

- Australian Institute of Health and Welfare (2022) *Built environment and health*, AIHW, Australian Government, accessed 12 August 2022.
- Australian Institute of Health and Welfare (2022) *The relationship between health risk factors and the neighbourhood environment*, AIHW, Australian Government, accessed 12 August 2022. doi:10.25816/jpx5-1f37.
- Australian Institute of Health and Welfare (2021) *Australian Burden of Disease Study: Impact and causes of illness and death in Australia 2018*, AIHW, Australian Government, accessed 12 August 2022. doi:10.25816/5ps1-j259.
- Australian Institute of Health and Welfare (2021) *Data update: Short-term health impacts of the 2019–20 Australian bushfires*, AIHW, Australian Government, accessed 12 August 2022.
- Australian Institute of Health and Welfare (2020) *Australian bushfires 2019–20: exploring the short-term health impacts*, AIHW, Australian Government, accessed 12 August 2022.
- Australian Institute of Health and Welfare (2011) *Health and the environment: a compilation of evidence*, AIHW, Australian Government, accessed 12 August 2022.

Ecosystem services are the benefits that society obtains from ecosystems, such as food, clean water and air. This review investigates the health benefits provided by 3 ecosystem services: air filtration, local climate regulation, and recreation. The review found ecosystem services provide many benefits to human health including respiratory, cardiovascular and mental health benefits.

aihw.gov.au

Stronger evidence,
better decisions,
improved health and welfare