Assessing outdoor air quality and temperature health impacts and benefits from green roofs: a case study for Genova, Italy.

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Title

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I would like to thank Ana Ascenso and Fábio Matos from UNaLab and Marta Ballocci for their help and my parents for their support and patience. I would also like give a special thanks to my supervisor Peter Roebeling for his guidance and detailed feedbacks.

Abstract

Cities are facing increasing populations and with increased human activities more emissions are being produced. These cause air pollution and heating within cities and, resulting, impacts on human health. A possible solution is making cities greener through nature-based solutions (NBS), such as green roofs, that provide ecosystem services, including provisioning, regulating and cultural services. Previous studies have examined the effects of green roofs on air quality, while other studies examined the effects of green roofs on temperature. However, a combination of the two is rarely explored, while the costs or benefits associated with green roofs have also mainly been studied separately. Hence, the objective of this research is **to assess the outdoor air quality and temperature health impacts and benefits from green roofs** with a case study for Genova, Italy. To this end, the impacts of green roofs on outdoor air quality and temperature were assessed using the Weather Research Forecasting model that incorporates chemistry (WRF-Chem) and the associated health impacts were assessed using AirQ+ and temperature-mortality curve. Finally, value transfers for green roof costs and avoided health costs (benefits) were used to assess the economic viability of green roofs using cost-benefit analysis. Results show that the largest impact of green roofs was on air quality concentrations, mainly O_3. The highest mortality is attributable to heatwaves (temperature), however green roofs prevent the most deaths attributed to O_3 emissions; hence, the largest health impact of green roofs was on air quality related health endpoints, mainly O_3. The sensitivity analysis shows that the net present value (NPV) is positive when the low (15.7 M€/year) monetary range of costs and the average (18.5 M€/year) or high (24.8 M€/year) monetary range of benefits are considered. Consequently, green roofs can be economically viable under certain conditions albeit that the costs fall upon the building owner and the health benefits are mainly societal.

This research is conducted in the context of the UNaLab project (https://unalab.eu/en).

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Abbreviations

BASE	baseline scenario
BCR	benefit-cost ratio
DALY	disability-adjusted life year
EC	European Commission (executive branch of the European Union)
EU	European Union
FCA	friction cost approach
HCA	human capital approach
HWM	heatwave mortality
NBS	nature-based solutions
NO_2	nitrogen dioxide
NPV	net present value
O_3	ozone
PM	particulate matter
RR	relative risk
SO_2	sulphur dioxide
UFORE	Urban Forest Effects
UHI	urban heat island effect
UN	United Nations
VOC	volatile organic compounds
WHO	World Health Organization
WRF-Chem	Weather Research Forecasting model with chemistry
WTP	willingness to pay
YLL	years of life lost

Contents

Chapter 1. Introduction

In this chapter the thesis research is introduced. In Section 1.1, the Problem statement that this research will address is discussed. In Section 1.2, the Objective and research questions are highlighted and Section 1.3 provides a Research outline.

1.1 Problem statement

Cities are facing increasing populations and with increased human activities more emissions are being produced. These cause air pollution and heating within cities (Miranda et al., 2016). The number of cities as well as their size is growing. This is due to migration from rural areas into urban (urbanization), in the hopes of improving standards of living, as well as an overall population growth (UN, 2019). Economic development and climate change are also drivers. This results in numerous pressures on the environment, in the form of land use changes, consumption of energy and the use of transportation concentrated within a build-up area. This noticeably increases emissions and impacts air quality (Liang & Gong, 2020). Heat is absorbed and albedo is reduced in build-up areas. This noticeably increases the temperature within cities (Oke, 1982).

Ambient (outdoor) air quality impacts human health, especially when the concentration of air pollutants is higher. Cities tend to have high concentrations of air pollutants, primarily due to energy consumption and vehicle traffic (Liang & Gong, 2020). Therefore, the World Health Organization (WHO, 2018a) has set guidelines for the most common air pollutants: particulate matter ($PM_{2.5}$ and PM_{10}), ozone (O_3), nitrogen dioxide (NO_2) and sulphur dioxide (SO_2). The presence of high concentrations of PM, for example, has been linked to increased hospital admissions (morbidity) due to asthma, chronic bronchitis, congestive heart failure, respiratory disease and cardiovascular disease. In more severe cases, PM also causes premature death (mortality; Silveira et al., 2016). The most vulnerable population to higher air pollutant concentrations are senior citizens, children and those with heart and lung conditions.

Ambient (outdoor) air temperature also impacts human health, especially when temperatures are higher. The urban heat island effect (UHI) explains that urban areas (cities) have higher temperatures than their surrounding (rural) areas. During summer months, this effect leads to more extreme heatwaves and prevents cooling during nights (Oke, 1982). The presence of extreme heat has been linked to increased hospital admissions (morbidity) due to (heat) stroke as well as worsening the conditions of chronic diseases, such as respiratory, renal (kidney) and diabetes (WHO, 2018b). In more severe cases, extreme heat also causes premature death (mortality; Anderson & Bell, 2009). Senior citizens are most vulnerable to higher temperatures.

Nature-based solutions (NBS) are considered desirable to tackle a wide range of environmental issues. NBS are “solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience” (European Commission, 2021b). Due to the lack of space within cities, a possible solution is altering the existing structures into ones that incorporate nature. There are three main types of NBS: improving the use or protection of natural ecosystems, improving the sustainability or function of managed ecosystems, and designing and managing newly-created ecosystems (Eggermont et al., 2015). Designing newly-created ecosystems include the establishment of blue-green spaces (urban parks), water storage (floodplains) and green built environment (green roofs).

Making cities greener through NBS provides ecosystem services; namely provisioning services, regulating and maintenance services, and cultural services (Haines-Young & Potschin, 2018). Provisioning ecosystem services are products obtained directly from the ecosystem. In the context of NBS, this includes food through the introduction of urban agriculture or community gardens. Regulating and maintenance ecosystem services are benefits gained from the regulation and maintenance of ecosystem processes. In the context of NBS, this includes the reduction of ground-level ozone (smog component) through the introduced green (vegetation) capturing and/or absorbing some air pollutants. Cultural ecosystem services are “non-material benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experience”(Millennium Ecosystem Assessment, 2005:p.3). In the context of NBS, this includes aesthetic and mental health benefits (spiritual enrichment) from connecting with nature through the introduction of urban green and blue-green spaces.

Within cities, there is an abundance of roofs and these spaces are rather underused. Vegetation can be planted on these roofs, thus turning them into green roofs. Green roofs have an effect on air quality, for example, shrubs, during their in-leaf season, are able to remove the same amount of PM_{10} as trees (Currie & Bass, 2008). When people are exposed to PM_{10} for a prolonged period of time, their lungs are affected causing asthma and bronchitis (van Zelm et al., 2008). A 1% decrease of PM_{10} can lead to an expected annual health benefit of 8.8 M€ (Silveira et al., 2016). Green roofs also have an effect on temperature, for example, short vegetation, even when unshaded (without trees), is able to lower temperatures through evaporative cooling (Bowler et al., 2010). In areas where heatwaves result in a great increase in mortality, the introduction of green roofs can substantially reduce mortality (Marvuglia et al., 2020).

Hence, previous studies have examined the effects of green roofs on air quality, while other studies examined the effects of green roofs on indoor and outdoor temperatures. However, a combination of the two is rarely explored. Furthermore, the costs associated with green roofs have also mainly been studied separately (i.e., either costs or benefits/avoided costs).

1.2 Objective and research questions

This research is conducted in the context of the UNaLab project (https://unalab.eu/en), which is co-funded by European Union's Horizon 2020 research and innovation programme. Within the UNaLab project, nature-based solutions (NBS) are used for the "development of smarter, more inclusive, more resilient and more sustainable urban communities" (UNaLab, 2021). These NBS are "co-created with and for local stakeholders and citizens" (UNaLab, 2021). Three front-runner cities, with a strong local engagement, have been selected within the project: Eindhoven (Netherlands), Tampere (Finland) and Genova (Italy). UNaLab aims to produce a handbook guide for all cities to follow in implementing NBS.

This research provides a case study for green roofs in Genova, Italy. At the time of this research, the UNaLab project is assessing the air quality and temperature impacts of NBS in Genova. This research aims to provide insights into the implementation of green roofs as a means of impacting the associated health through outdoor air quality and temperature, and quantifying the consequent economic benefits. Through stakeholder mapping workshops, residential areas have been identified as a problematic location that will benefit from the implementation of NBS, such as green roofs.

The objective of this research is **to assess the outdoor air quality and temperature health impacts and benefits from green roofs** with a case study for Genova, Italy.

The objective will be reached by answering the following specific research questions.

1. What are the impacts of green roofs on outdoor air quality and temperature?
2. What are the air quality and temperature health impacts of green roofs?
3. What are the investment and maintenance costs and health benefits of green roofs?
4. What is the economic viability of implementing green roofs in Genova, Italy?

Study boundaries: Indoor air quality and temperature also affect human health, however these impacts will not be discussed within the scope of this research. Moreover, beyond the scope of this research are also the effect on mental health and indirect effects, such as increased risk of drowning during heatwaves. Other benefits of green roofs, such as water retention, energy consumption and/or noise insulation, are also not considered within this research. Therefore, future mentions of air quality and temperature are referring to solely outdoor, and health effects are referring solely to direct effects on physical health, unless otherwise stated.

1.3 Research outline

This research has five chapters;

Chapter 1 is an Introduction to the research that provides an overview of how urban areas are dealing with higher air pollution and higher temperatures, and how NBS, such as green roofs, can tackle such problems. The economic implications of introducing green roofs in Genova, Italy and the subsequent health impacts are worth exploring.

Chapter 2 is a Literature Review, where a rapid systematic literature review is conducted and the main findings are reported. A summary of the discussion on the valuation of illness and life is also included.

Chapter 3 is the Methodology, where an integrated assessment approach is used to reach the objective of this research as all four specific research questions are answered.

- Weather Research Forecasting model with chemistry (WRF-Chem) is used to assess the impacts of green roofs on outdoor air quality and temperature (research question 1) by comparing air quality and temperature values from the baseline (BASE) scenario to the green roof (NBS) scenario;
- AirQ+ and temperature-mortality curve are used to assess the air quality and temperature health impacts of green roofs, respectively (research question 2), by calculating the number of health endpoint cases in both scenarios;
- Value transfers are used to assess the investment and maintenance costs and the health benefits of green roofs (research question 3) by assigning values found in literature to the two scenarios; and
- Cost-benefit analysis is used to assess the economic viability of green roofs (research question 4) by comparing the costs of introducing green roofs and the benefits of avoided health endpoint costs due to green roofs.

Chapter 4 provides Results of the BASE scenario with context and the Results found for answering each specific research question.

Chapter 5 provides a Discussion and conclusions, with a summary of the main findings and policy recommendations. Limitations and suggests for improvement are also noted.

Chapter 2. Literature Review

In this chapter the currently available literature is explored. A rapid systematic literature review (Section 2.1) was conducted on the topic of green roofs, air quality and temperature, health and benefit. This is followed by a summary of the discussion on health endpoint valuation (Section 2.2).

2.1 Systematic literature review

A rapid systematic literature review was conducted to provide an overview of the available peer-reviewed publications that were available at the time of writing (July 2021) on the topics of this research: green roofs, air quality and temperature, health and benefit. The literature search was conducted in Scopus (www.scopus.com), which is an online database of peer-reviewed publications. Scopus was able to provide a general overview of the available knowledge, which was sufficient for the purpose of this rapid systematic literature review, and therefore other databases as well as printed publications were not considered. Searched keywords and the number of their yielded publications can be found in Table 1. It should be noted that any publications of the same title and author(s) were considered duplicates and only the originals were counted.

In the planning stage, it was discovered that a preliminary Scopus search of these domain terms were relevant to identify the knowledge surrounding the objective of this research; to assess outdoor air quality and temperature health impacts and benefits from green roofs. No further restrictions were applied to this preliminary search. Due to the limited number of publications, it was decided to conduct two separate searches; focusing on topic of green roofs, air quality, health and benefits, and focusing on the topic of green roofs, temperature, health and benefits.

Inclusion/exclusion criteria

At this stage of the systematic literature review, both searches were exhaustive. Any irrelevant publications were disregarded during later steps. There were no restrictions placed on the searches, for example in the form of language or publication date range. The Boolean “OR” was used to include synonyms and/or more specific examples for each domain along with the original, more general domain keyword. Furthermore, to avoid cultural spelling differences within the searches the scientific symbols were used as keywords, for example SO2 was used as a keyword rather than sulphur dioxide and/or sulfur dioxide.

Table 1. Searched keywords and the number of publications.

Search	Searched keywords					Number of publications
	Green roofs	Air Quality	Temperature	Health	Benefit	
1	“green roof*”	“air qualit*”	“temperature*”	“health*”	“benefit*”	7
2	“green roof*”	"air pollution*" OR "air qualit*" OR "NOx" OR "nitr*" OR "PM*" OR "particulate matter*" OR "O3" OR "ozone" OR "SO2" OR " sulphur" OR "sulfur"	"temperature" OR "heat*" OR "thermal*" OR "UHI" OR "urban heat island"	"health*" OR "mortal*" OR "diseas*"	"benefit*" OR "cost*" OR "economic*"	27
3	“green roof*”	"air pollution*" OR "air qualit*" OR "NOx" OR "nitr*" OR "PM*" OR "particulate matter*" OR "O3" OR "ozone" OR "SO2" OR " sulphur" OR "sulfur"	-	"health*" OR "mortal*" OR "diseas*"	"benefit*" OR "cost*" OR "economic*"	42
4	“green roof*”	-	"temperature" OR "heat*" OR "thermal*" OR "UHI" OR "urban heat island"	"health*" OR "mortal*" OR "diseas*"	"benefit*" OR "cost*" OR "economic*"	71
5	“green” AND “roof*”	"air pollution*" OR "air qualit*" OR "NOx" OR "nitr*" OR "PM*" OR "particulate matter*" OR "O3" OR "ozone" OR "SO2" OR " sulphur" OR "sulfur"	-	"health*" OR "mortal*" OR "diseas*"	"benefit*" OR "cost*" OR "economic*"	53
6	“green” AND “roof*”	-	"temperature" OR "heat*" OR "thermal*" OR "UHI" OR "urban heat island"	"health*" OR "mortal*" OR "diseas*"	"benefit*" OR "cost*" OR "economic*"	92

2.1.1 Air quality literature search

This section presents the results from the air quality literature search; the searched keywords used are from search number 5 in Table 1. There are a total of 53 unique publications that come-up within the Scopus search and 24 of those publications are considered relevant.

Figure 1 shows that research on air quality health impacts and costs is becoming more popular, however it is still a relatively new topic that has emerged in 2006.

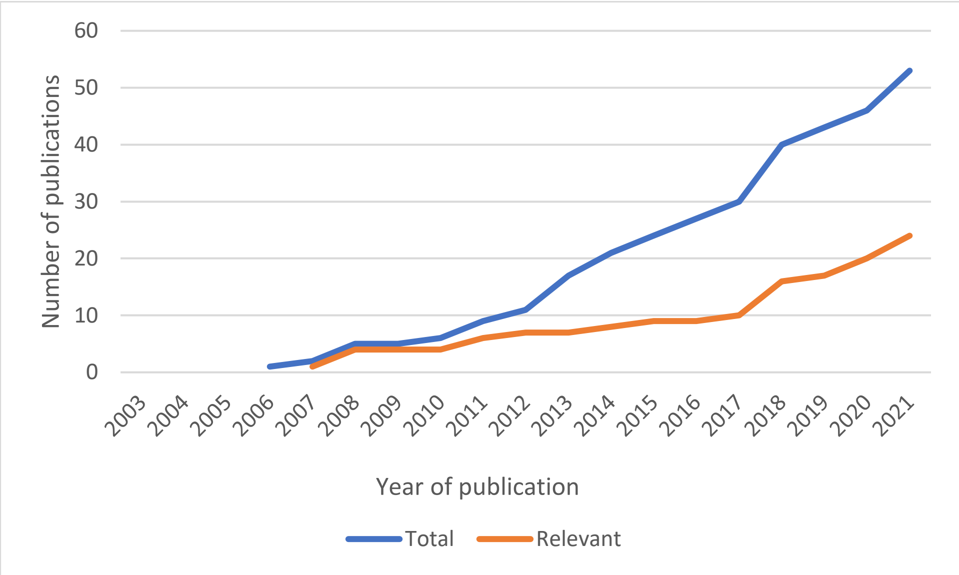

Figure 1. Evolution of publications within the air quality literature search.

Figure 2 shows that the term “green roof” is mentioned in the title, abstract or as a keyword within 40 of 53 publications that have come-up within the Scopus search, and in 19 of 24 publications that are relevant for this research. The term “green wall” or “green façade” is not used as often, although it is a similar method to green roofs for making buildings physically green. Furthermore, the term “green space” and “nature-based solution” is only used by 3 relevant publications. This means that there is a greater focus on “green” as a general concept rather than a specific NBS method. The focus of this research is on green roofs and thus the majority of relevant publications that use the term “green” are referring to green roofs. Not all publications that use the term “green roof” were found to be relevant to this research, which means that their main focus is on another topic and not on the connection with air quality.

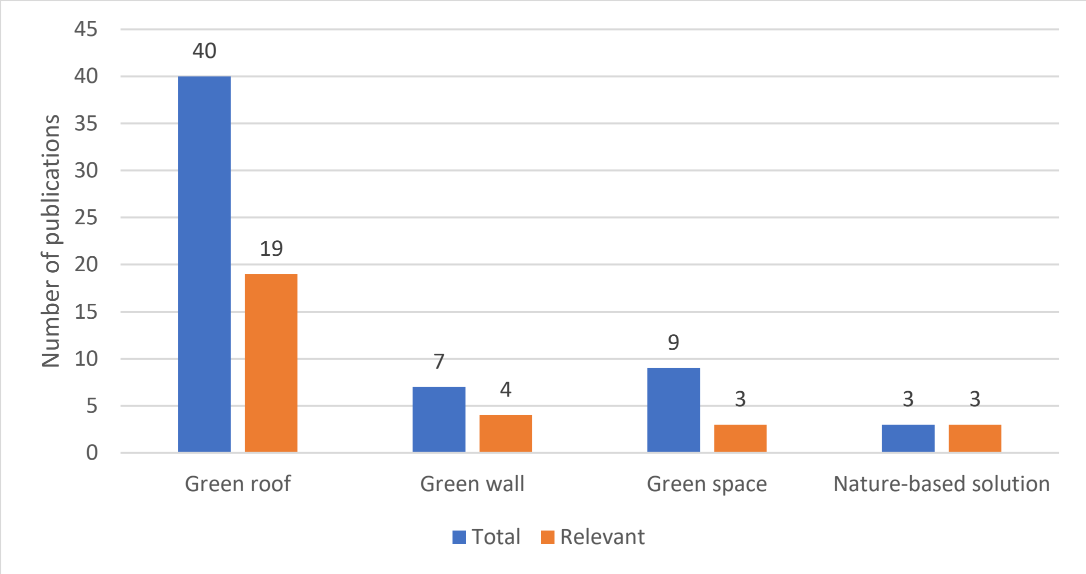

Figure 2. Green roofs keywords within the air quality literature search.

Figure 3 shows that the terms "air pollution" and "air quality" are used more frequently than specific pollutants (in both their written-out and scientific symbol forms). This highlights a research/knowledge gap into the exploration of specific air pollutants and their relation to health impacts and costs.

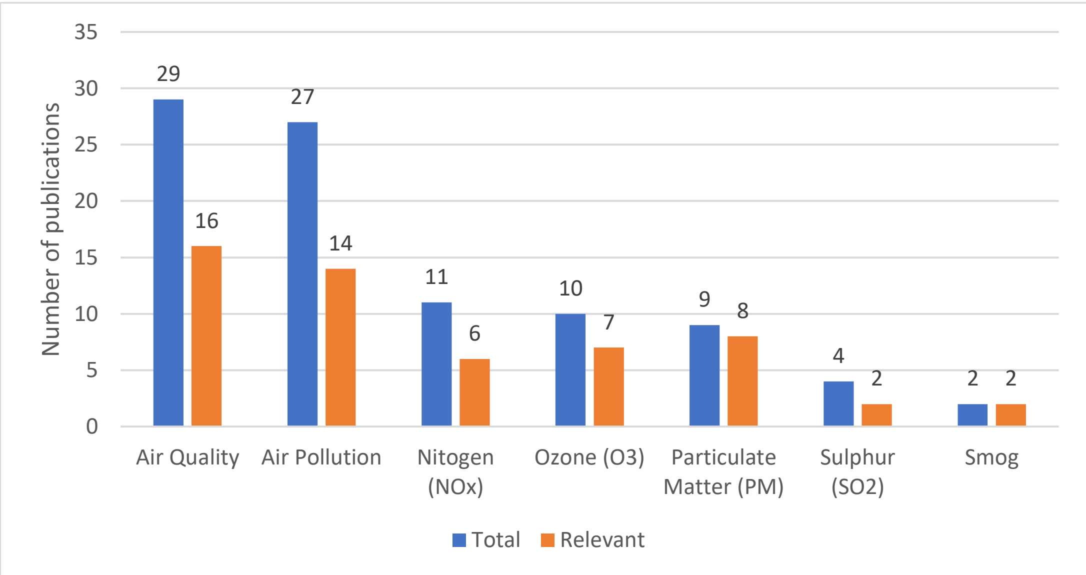

Figure 3. Air quality keywords within the air quality literature search.

Figure 4 shows that the term "health" is mentioned in almost all publications. However, specific consequences to poor health are mentioned rarely; no mention of morbidity, 4 mentions of mortality and 2 mentions of hospital (admission). This highlights a research/knowledge gap into the exploration of more specific consequences and/or a quantification of health impacts and costs related to air pollution.

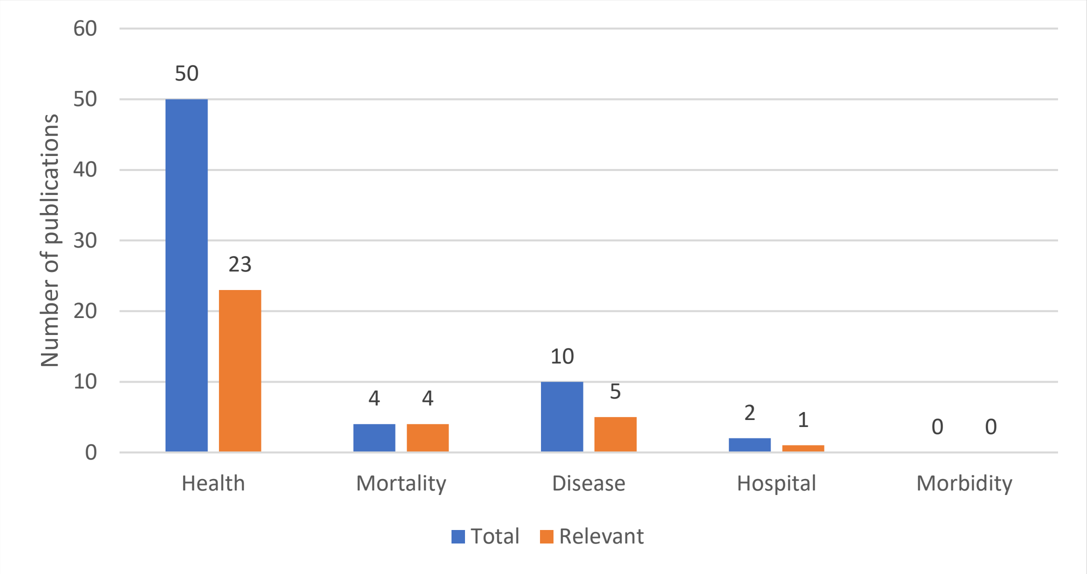

Figure 4. Health keywords within the air quality literature search.

Figure 5 shows the different health issues related to air pollution (Silveira et al., 2016), there are 8 main terms that were explored. “Cardiovascular”, “respiratory”, “lung” and “asthma” are the most mentioned health issues terms. Whereas, “cough” and “cancer” are not mentioned by any of the publications. This further highlights a research/knowledge gap into the exploration of more specific health issues related to air pollution.

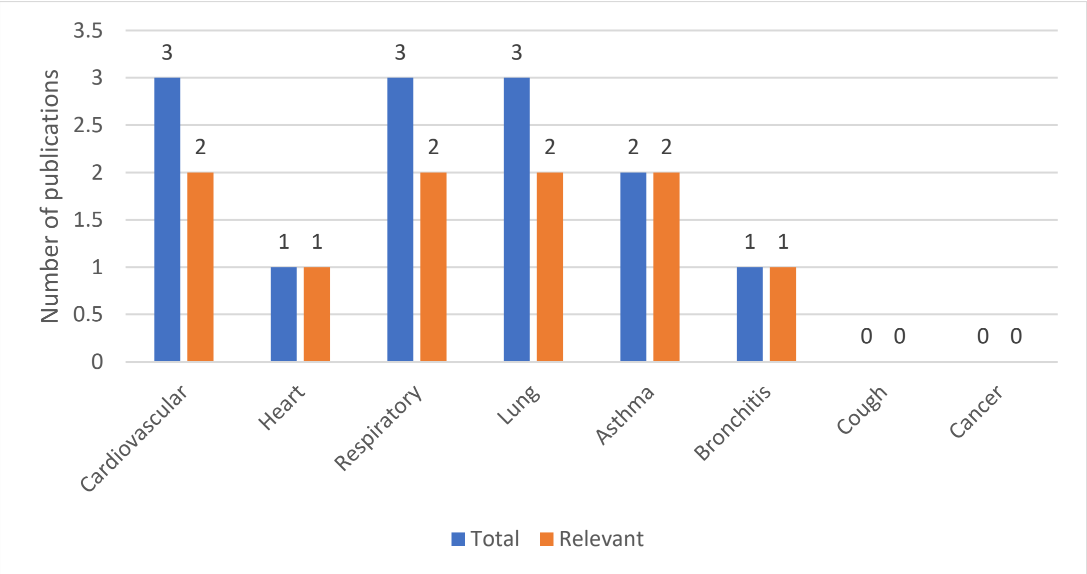

Figure 5. Specific health issues related to air pollution within the air quality literature search.

Figure 6 shows that the term "benefit" is mentioned in 40 publications that have come-up within the Scopus search and in 18 publications that are relevant for this research. The term "cost" is mentioned in 21 publications that have come-up within the Scopus search and in 7 publications that are relevant for this research. This shows that there is a greater focus on benefit rather than on cost assessments. "Cost-benefit analysis" is mentioned in 6 publications that have come-up within the Scopus search and in 4 publications that are relevant for this research. This shows that only a few studies compare costs and benefits of health impacts related to air quality.

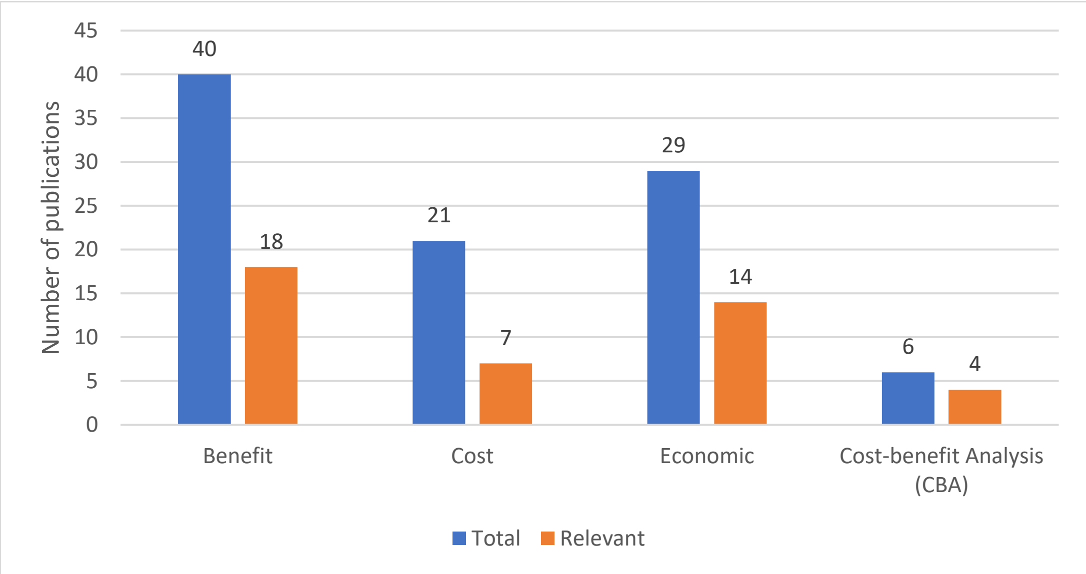

Figure 6. Benefit keywords within the air quality literature search.

2.1.2 Temperature literature search

This section presents the results from the temperature literature search; the searched keywords used are from search number 6 in Table 1. There is a total of 92 unique publications that come-up within the Scopus search and 47 of those publications are considered relevant.

Figure 7 shows that research on temperature health impacts and costs is becoming more popular, however it is still a relatively new topic with relevant publications emerging in 2008.

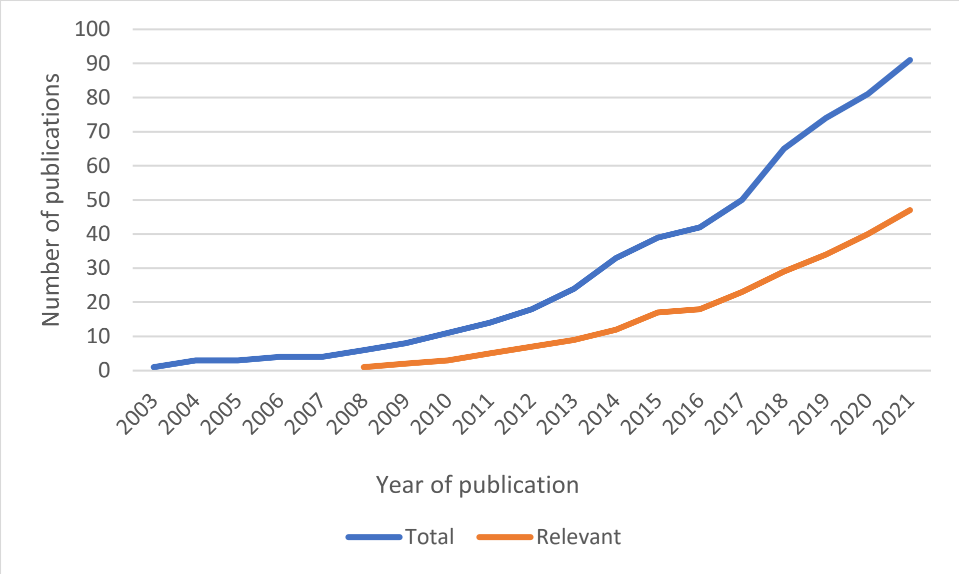

Figure 7. Evolution of publications within the temperature literature search.

Figure 8 shows that the term “green roof” is only mentioned in 69 of 92 publications that have come-up within the Scopus search, and in 42 of 47 publications that are relevant for this research. The term “green wall” or “green façade” is not used as often, although it is a similar method to green roofs for making buildings physically green. Furthermore, the terms “green space” and “nature-based solution” are used even less. This means that there is a greater focus on “green” as a general concept rather than a specific NBS method. The focus of this research is on green roofs and thus the majority of relevant publications that use the term “green” are referring to green roofs. Not all publications that use the term “green roof” were found to be relevant to this research, which means that their main focus is on another topic and not on the connection with temperature.

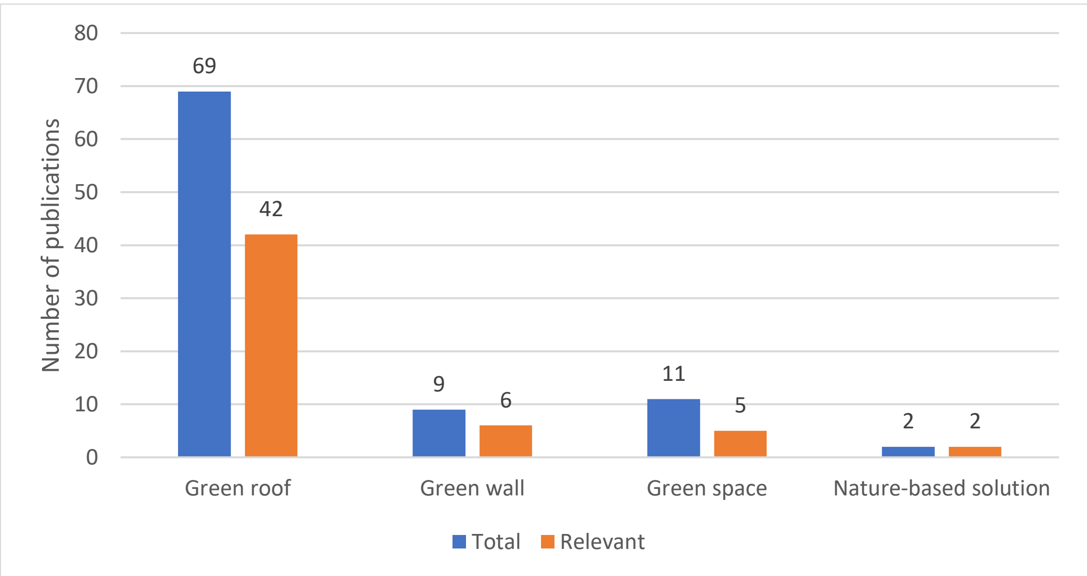

Figure 8. Green roofs keywords within the temperature literature search.

Figure 9 shows that the term “heat” is used more often than the terms “temperature” and “thermal”. This means that publications focus on heat rather than temperature as a whole. However, the more specific consequences of higher temperatures; urban heat island effect and heatwaves, are mentioned in only 9 and 7 publications respectively. This highlights a research/knowledge gap into the exploration of temperature in relation to health impacts and costs.

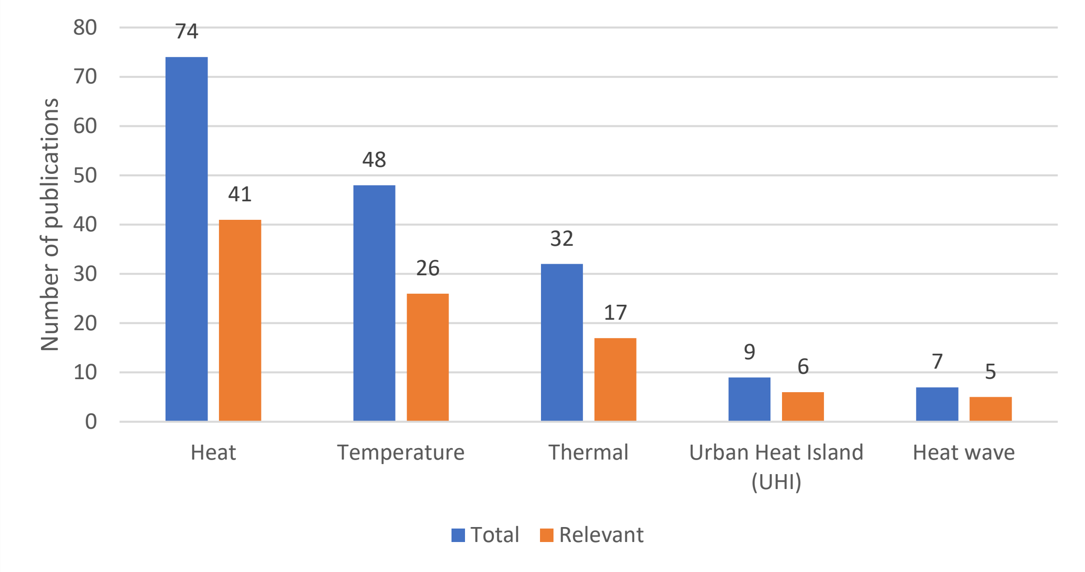

Figure 9. Temperature keywords within the temperature literature search.

Figure 10 shows that the term “health” is mentioned in almost all publications. However, specific consequences to poor health are not mentioned as often; 2 mentions of morbidity, 15 (12 in relevant) mentions of mortality and 4 (1 in relevant) mentions of hospital (admission). This highlights a research/knowledge gap into the exploration of more specific consequences and/or a quantification of health impacts and costs related to temperature.

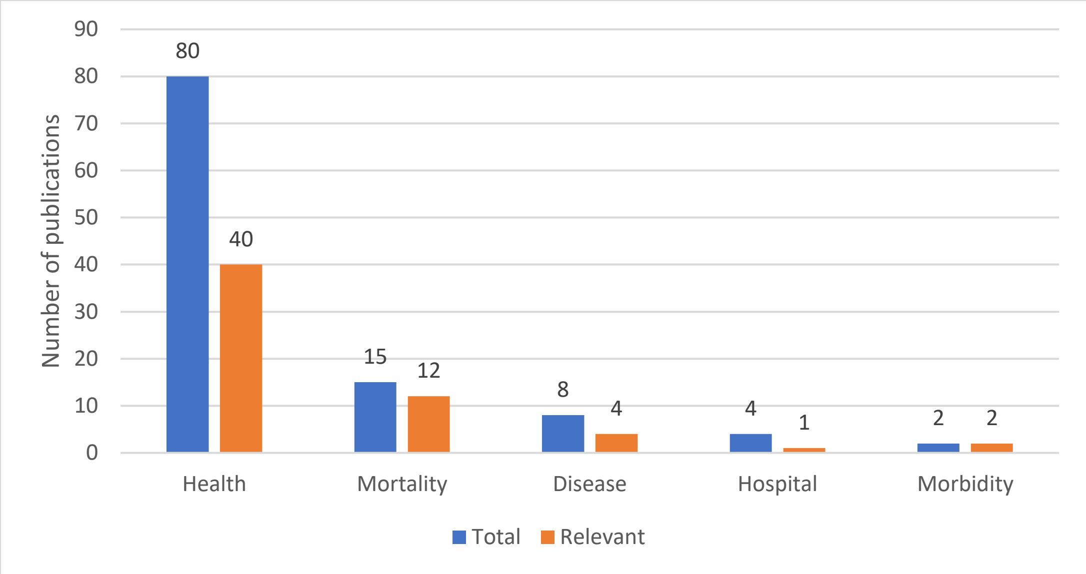

Figure 10. Health keywords within the temperature literature search.

Figure 11 shows the different health issues related to extreme heat temperatures (WHO, 2018b), there are 8 main terms that were explored. “Cardiovascular”, “respiratory” and “heart” are the health issues terms mentioned at least once. Whereas, “stroke”, “dehydration”, “cramps”, “renal” and “diabetes” are not mentioned by any of the publications. This further highlights a research/knowledge gap into the exploration of more specific health issues related to extreme heat temperatures.

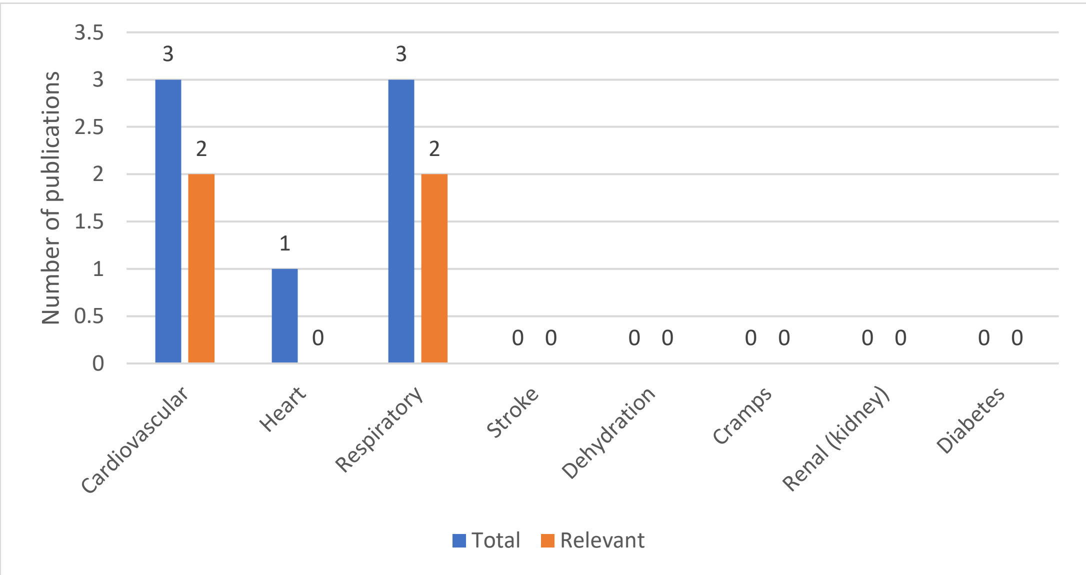

Figure 11. Specific health issues related to extreme heat within the temperature literature search.

Figure 12 shows that the term “benefit” is mentioned in 65 publications that have come-up within the Scopus search and in 35 publications that are relevant for this research. The term “cost” is mentioned in 37 publications that have come-up within the Scopus search and in 18 publications that are relevant for this research. This shows that there is a greater focus on benefit rather than on cost assessments. “Cost-benefit analysis” is mentioned in 8 publications that have come-up within the Scopus search and in 4 publications that are relevant for this research. This shows that only a few studies compare costs and benefits of health impacts related to temperature.

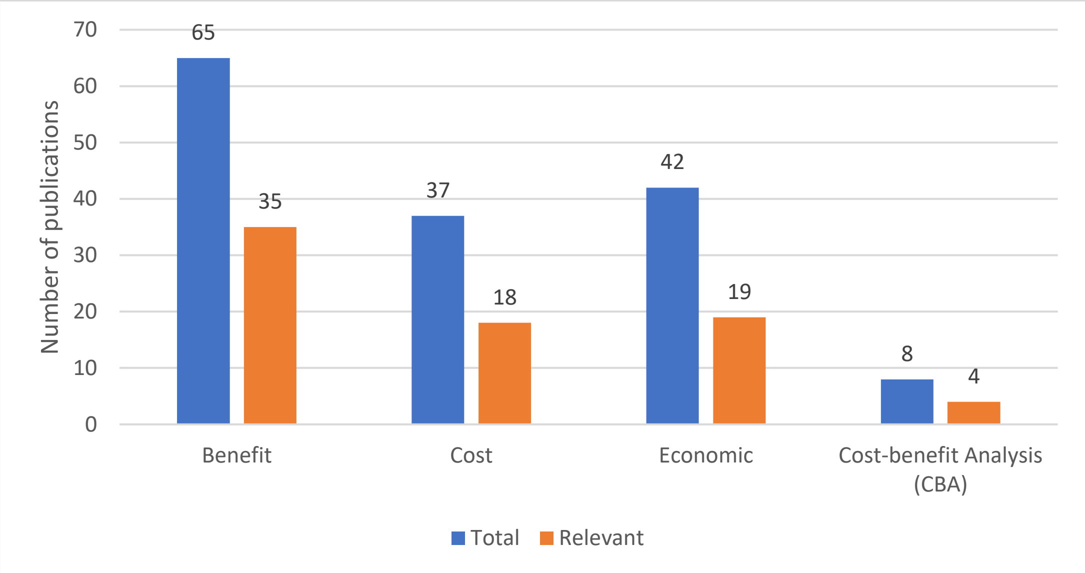

Figure 12. Benefit keywords within the temperature literature search.

2.1.3 Air quality and temperature literature search

This section presents the results for publications that have come-up within both the Scopus searches; the air quality literature search (search number 5 in Table 1) and the temperature literature search (search number 6 in Table 1). There is a total of 31 unique publications and 14 of those publications are considered relevant.

Figure 13 shows that research on air quality health impacts and costs and on temperature health impacts and costs is becoming more popular, however it is still a relatively new topic that has emerged in 2008.

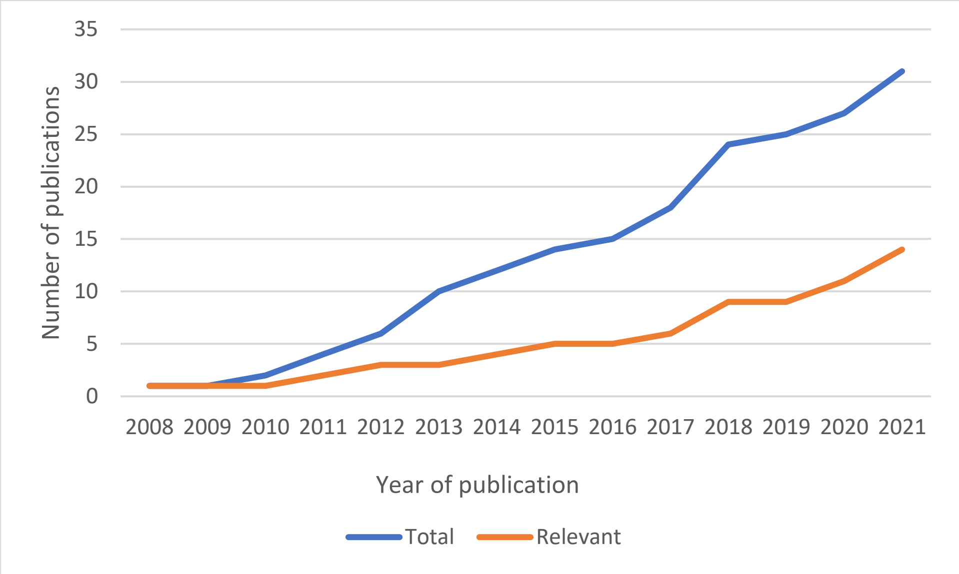

Figure 13. Evolution of publications within both the air quality literature search and the temperature literature search.

Figure 14 shows that the term “green roof” is mentioned in the title, abstract or as a keyword within 25 of 31 publications that have come-up within the Scopus search, and in 12 of 14 publications that are relevant for this research. The term “green wall” or “green façade” is not used as often, although it is a similar method to green roofs for making buildings physically green. Furthermore, the term “green space” and “nature-based solution” is only used by 1 and 2 relevant publications, respectively. This means that there is a greater focus on “green” as a general concept rather than a specific NBS method. The focus of this research is on green roofs and thus the majority of relevant publications that use the term “green” are referring to green roofs. Not all publications that use the term “green roof” were found to be relevant to this research, which means that their main focus is on another topic and not on the connection with air quality and temperature.

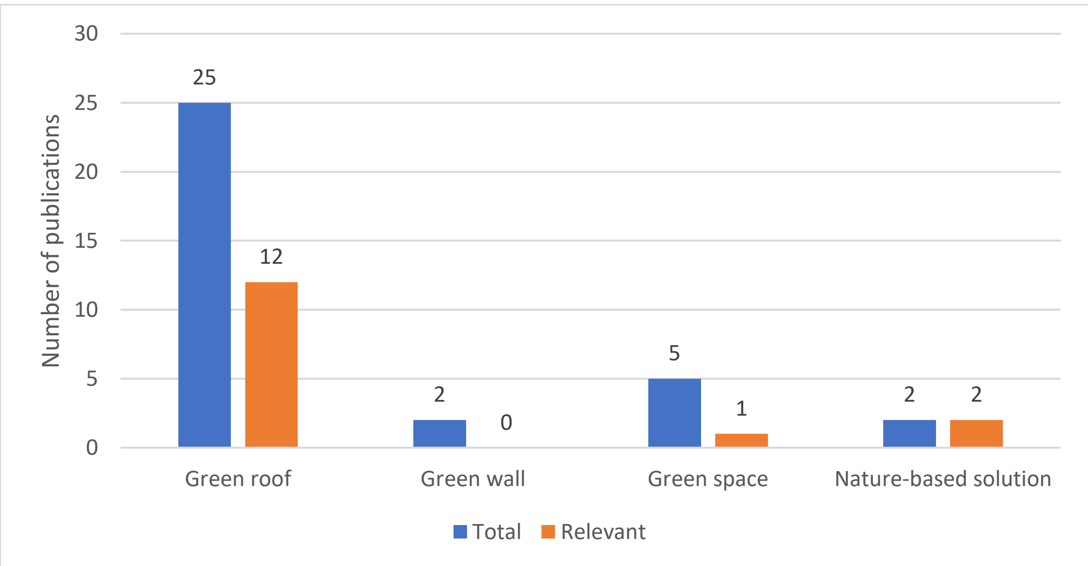

Figure 14. Green roofs keywords within both the air quality literature search and the temperature literature search.

Figure 15 shows that the terms "air pollution" and "air quality" are used more frequently than specific pollutants (in both their written-out and scientific symbol forms). This highlights a research/knowledge gap into the exploration of specific air pollutants and their relation to health impacts and costs.

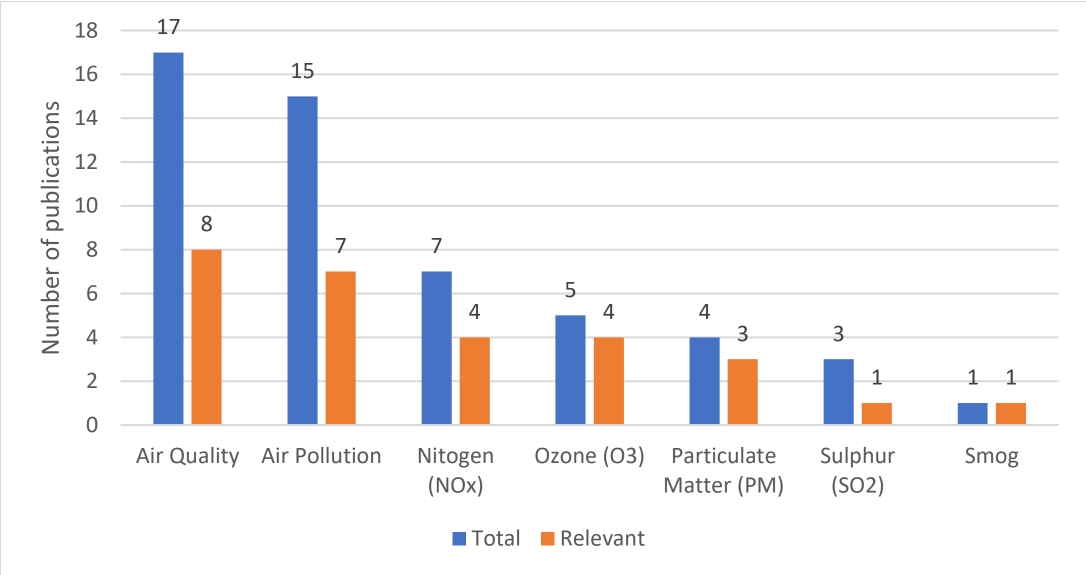

Figure 15. Air quality keywords within both the air quality literature search and the temperature literature search.

Figure 16 shows that the term "heat" is used more often than the terms "temperature" and "thermal". This means that publications focus on heat rather than temperature as a whole. However, the more specific consequences of higher temperatures; urban heat island effect and heatwaves, are mentioned in only 1 and 2 publications respectively. This highlights a research/knowledge gap into the exploration of temperature in relation to health impacts and costs.

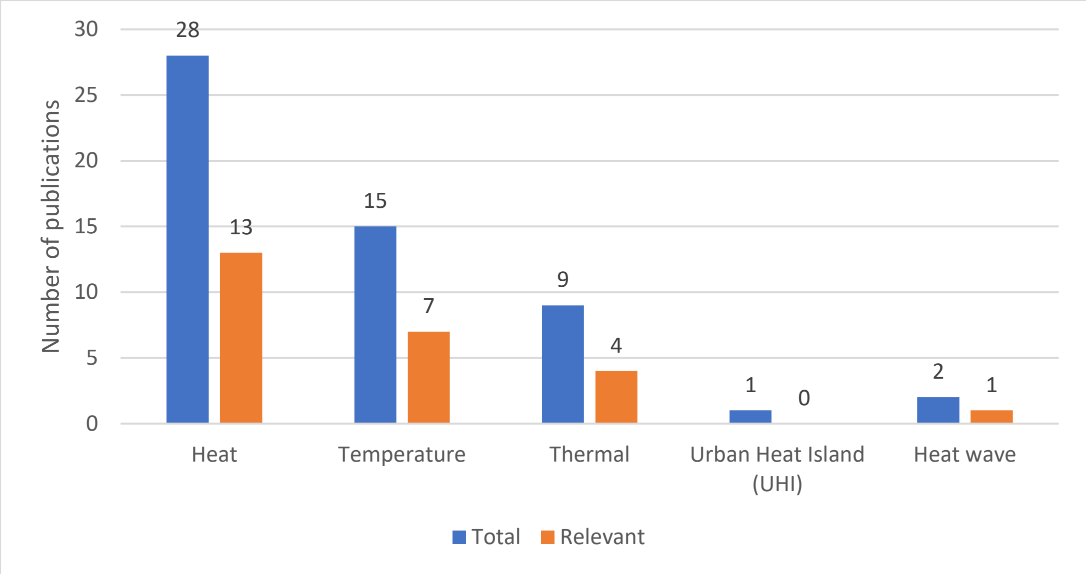

Figure 16. Temperature keywords within both the air quality literature search and the temperature literature search.

Figure 17 shows that the term "health" is mentioned in almost all publications. However, specific consequences to poor health are mentioned rarely; no mention of morbidity, 4 mentions of mortality and 1 mention of hospital (admission). This highlights a research/knowledge gap into the exploration of more specific consequences and/or a quantification of health impacts and costs related to air pollution and extreme heat.

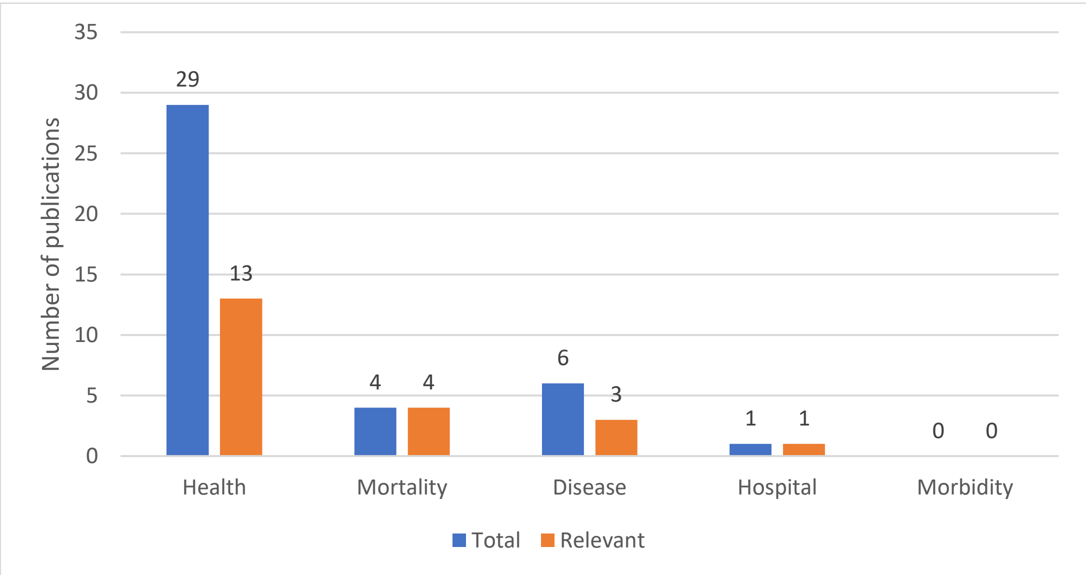

Figure 17. Health keywords within both the air quality literature search and the temperature literature search.

Figure 18 shows the different health issues related to air pollution (Silveira et al., 2016) and extreme heat temperatures (WHO, 2018b). “Cardiovascular” and “respiratory” are the most mentioned health issues terms and are also the two health issues terms related to both air pollution and extreme heat temperatures. Related solely air pollution health issues, the terms “lung” and “asthma” are mentioned once by publications that are relevant for this research and “bronchitis” is not mentioned by any of the publications. Related solely to extreme heat temperatures health issues, the terms “stroke”, “dehydration” and “cramps” are not mentioned by any of the publications. This further highlights a research/knowledge gap into the exploration of more specific health issues related to air pollution and extreme heat temperatures.

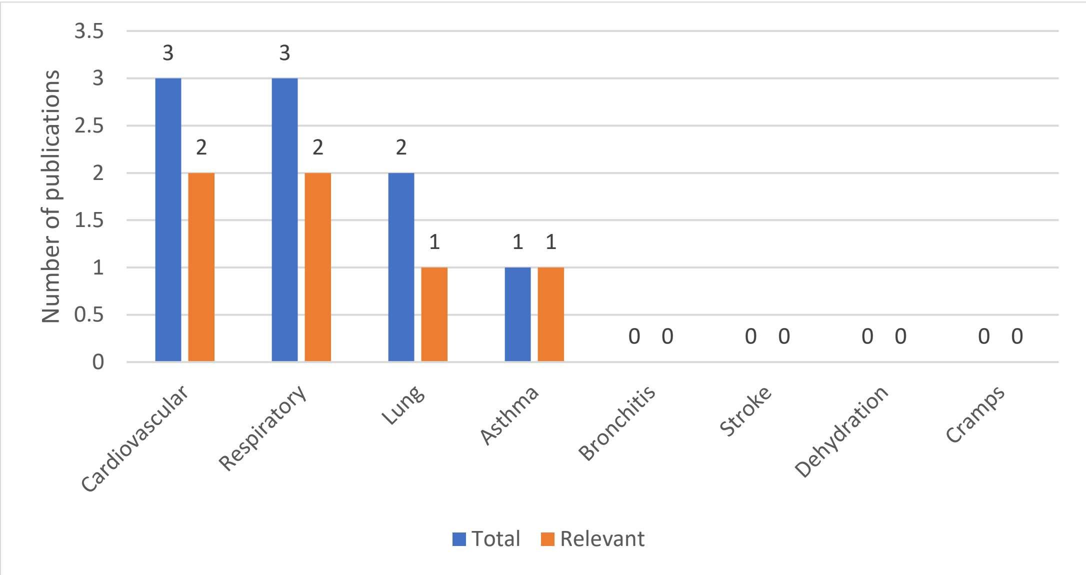

Figure 18. Specific health issues related to air pollution and extreme heat within both the air quality literature search and the temperature literature search.

Figure 19 shows that the term “benefit” is mentioned in 26 publications that have come-up within the Scopus search and in 12 publications that are relevant for this research. The term “cost” is mentioned in 11 publications that have come-up within the Scopus search and in 3 publications that are relevant for this research. This shows that there is a greater focus on benefit rather than on cost assessments. “Cost-benefit analysis” is mentioned in 5 publications that have come-up within the Scopus search and in 3 publications that are relevant for this research. This shows that only a few studies compare costs and benefits of health impacts related to air quality and temperature.

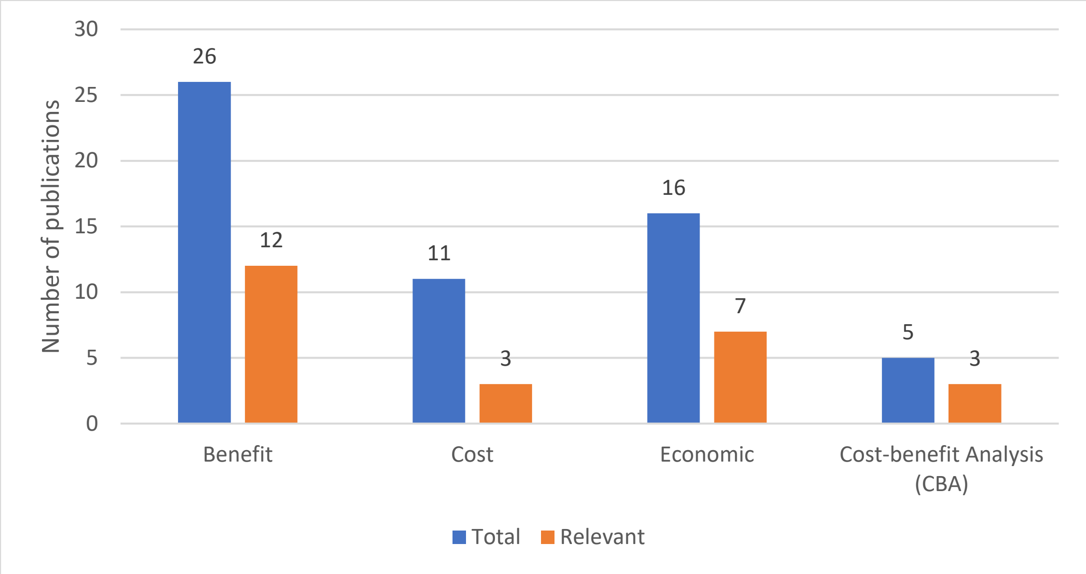

Figure 19. Benefit keywords within both the air quality literature search and the temperature literature search.

2.1.4 Main findings

This section highlights the main findings from the systematic literature review. The main impacts of green roofs are energy (consumption), water, noise and air quality. Some publications have also focused on the construction/engineering, architecture or agriculture, with a focus on the soil and plants. Only the publications that have a direct focus on air quality and/or temperature were deemed relevant for this research.

In the Air quality literature search (Section 2.1.1); Rowe (2011) published a review of studies that have calculated specific air pollutant reductions due to green roofs and highlights that the difference between those calculations are mainly due to the choice of plant species; different abilities to absorb pollutants in certain conditions (for example, dormant during winter). Another relevant publication is by Currie & Bass (2008), who simulated effects in a model using Urban Forest Effects (UFORE). They found that combining grass, shrubs and trees can yield the highest air pollution removal; 7.01 Mg NO_2 and 13.8 Mg O_3 in Midtown per annum.

In the Temperature literature search (Section 2.1.2); He et al. (2020) did a model case study. They found that in the summer, green roofs reduce temperatures by 0.35°C and in the winter, there are no effects on temperature. Furthermore, they found that cooler summers can reduce heat-wave mortality by 0.21%. Another relevant publication is by Sproul et al. (2014), who did an analysis of the life cycle of green roofs under three different conditions; normal (black) roofs, roofs painted white and green roofs. They found that white roofs cool down more effectively than green roofs, however they still recommend green roofs as other local environmental benefits should be considered.

In the Air quality and temperature literature search (Section 2.1.3); Knight et al. (2021) did a systematic review. Their focus was on green areas, which includes parks, gardens and green roofs, and found that on average temperature decreases by 2°C, NO_2 by 1 standard deviation unit and there was not a clear impact on O_3. Furthermore, they found that impacts can be measured up to 1.25km from the green area. Another relevant publication is by Teotónio et al. (2018), who developed a methodology for a green roof cost-benefit analysis with a case study. They divided the analysis into three levels: financial, economic and socio-environmental. They found that intensive green roofs in Lisbon, Portugal can provide 506 €/m² of social benefit and 218 €/m² of costs, while extensive green roofs provide 71 €/m² of social benefit and 100 €/m² of costs.

From the systematic literature review; it is clear that green roofs help reduce NO_2 emissions and reduce temperature, however the extent of this impact varies and the impact on O_3 is uncertain. The air quality and temperature health impacts of green roofs are not fully explored within the relevant publications. There are numerous benefits of green roofs, however health impacts have not been studied separately and therefore the exact contribution to benefits is not known. The implementation of green roofs is potentially economically viable under certain conditions, such as an intensive green roof with a combination of grass, shrubs and trees.

2.2 Valuation of illness and life

This research considers air quality and temperature health benefits from green roofs in the form of avoided health endpoint costs. The costs of health endpoints can be rather subjective, especially when valuing mortality. In literature, there are mainly two established methods; willingness to pay (WTP) and years of life lost (YLL). As these two methods focus on different aspects, it has been suggested that an alternative approach may be more complete. The cost-of-illness approach incorporates direct, indirect and intangible costs (Pervin et al., 2008). Direct costs are associated with expenses for, for example, medication, treatments, doctor examinations and/or hospital admission. Indirect costs are associated with loss of productivity. Intangible costs are associated with the pain and suffering related to the health endpoint.

WTP incorporates direct medical expenses and intangible costs. WTP is the amount an individual is willing to pay for avoiding the risk of the health endpoint (Boardman et al., 2018). For example, the amount an individual is willing to trade-off for not experiencing cancer. WTP is influenced by numerous factors (such as income, country, culture). For example, the amount an individual with a lower income is willing to pay may seem lower compared to the amount of an individual with a higher income, however in both cases the individual may be willing to pay everything they have.

YLL incorporates indirect costs. YLL determines a certain productivity for each individual during their working years, assuming that the individual reaches their life expectancy. If the individual dies prior to their retirement, the number of years that they could have still been working is multiplied by the productivity to give a value of lost productivity to society. This approach takes into consideration age and results in higher costs for the mortality of a younger individual. Although YLL focuses on premature mortality, there are several alternatives of the same principles for morbidity, such as the disability-adjusted life year (DALY) that measures the (short-term to permanent) disease burden on productivity (WHO, 2013).

Productivity losses can be estimated according to the human capital approach (HCA) or the friction cost approach (FCA). While the HCA considers and values the entire period of absence from work due to illness, the FCA reflects only the productivity loss prior to the ill worker being replaced, thus the true cost of productivity loss for employers (Pearce, 2016). Hence, the HCA estimates higher indirect costs as compared to the FCA.

Chapter 3. Methodology

In this chapter the methodology to address the overall aim of this research is described through the specific research questions (see Section 1.2). An integrated assessment approach is developed (see Figure 20 for the relationship flow diagram). Section 3.1 describes the method of using Weather Research Forecasting model with chemistry (WRF-Chem) for Assessing the impacts of green roofs on outdoor air quality and temperature. Section 3.2 describes the method of using AirQ+ and temperature-mortality curve for Assessing the air quality and temperature health impacts of green roofs. Section 3.3 describes the method of using value transfers for Assessing the investment and maintenance costs and health benefits of green roofs. Section 3.4 describes the method of using cost-benefit analysis for Assessing the economic viability of green roofs in Genova.

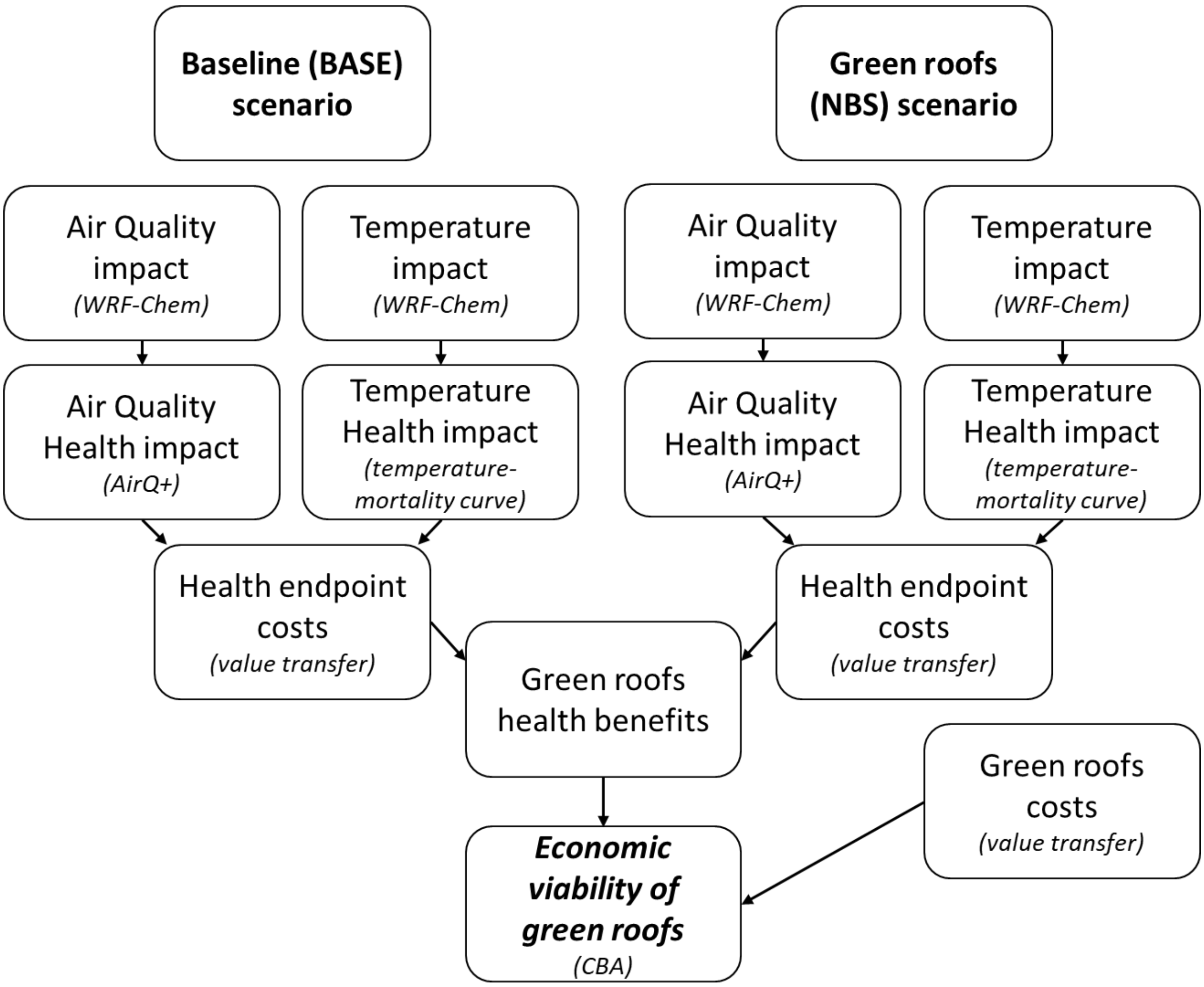

Figure 20. Integrated assessment to assess the economic viability of green roofs flow diagram.

3.1 Assessing the impacts of green roofs on outdoor air quality and temperature

The impacts of green roofs on outdoor air quality and temperature were assessed by UNaLab using the Weather Research Forecasting model that incorporates chemistry (WRF-Chem). The relationship between input and output data and how these assess the impacts of green roofs is shown in Figure 21.

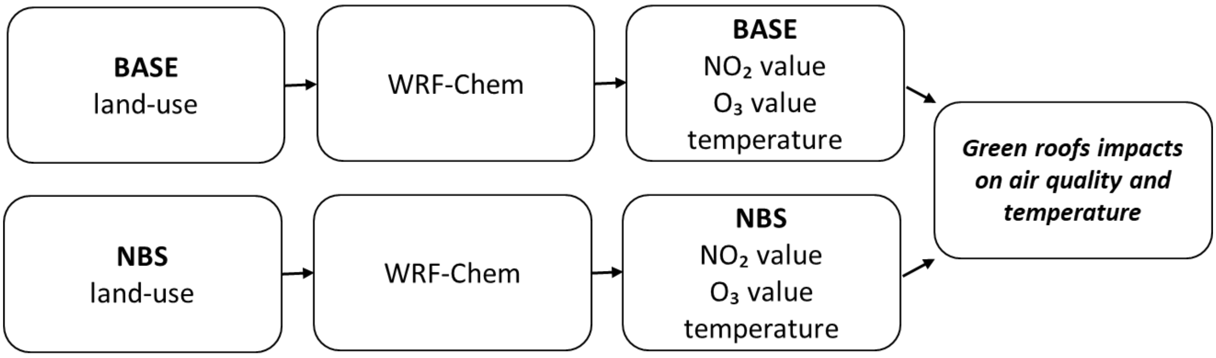

Figure 21. Impacts of green roofs on air quality and temperature flow diagram.

WRF-Chem is an online modelling system operating at the mesoscale (Grell et al., 2005). It is able to provide forecasts of air pollutant concentrations and temperature (and other meteorological indicators) depending on the component schemes that have been selected. The model structure and equations are explained in detail in Skamarock et al. (2008) and a user guide with instructions is available on the model's website: https://ruc.noaa.gov/wrf/wrf-chem/Users_guide.pdf.

WRF-Chem considers land use characteristics among other inputs that are specific to the region being modelled. For comparison, two scenarios were modelled; a baseline scenario (BASE) of the current (2013) situation and a NBS scenario where green roofs were implemented. Genova was separated into 1km² grid cells (total of 282 grid cells: see Figure 22). For the baseline scenario, the dominant land use of each grid cell was used as input data. For the NBS scenario, the land use of two grid cells (grid cell number 655 and 695, highlighted in green in Figure 22) was altered to represent grass, which simulated the presence of green roofs. For the best results, the entire grid cell area (100%) was altered. The selection of where to implement green roofs was done by UNaLab together with the residents of Genova and other stakeholders.

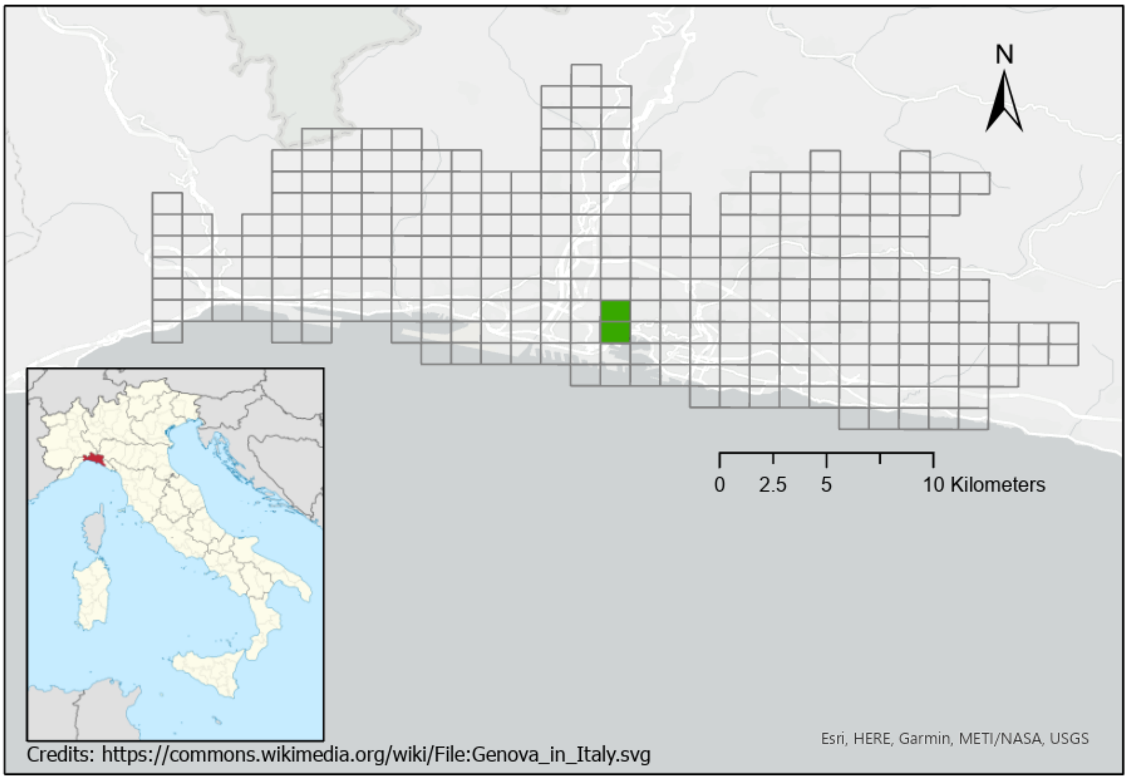

Figure 22. WRF-Chem grid cells (1km²) and green roofs location (in green) for Genova, Italy.

For both scenarios, the WRF-Chem was calculated over a representative week (28th July to 3rd of August, 2013). This representative summer week was selected based on consecutively having the warmest days and 2013 being a year with the smallest anomalies in climate conditions (temperature and precipitation) within the period 2012-2016. The output data, in terms of maximum and minimum air pollutant values (NO_2 and O_3) and mean temperature, was used as input data for Assessing the air quality and temperature health impacts of green roofs (see Section 3.2).

It should also be noted that the presence of certain air pollutants has an effect on the concentrations of other pollutants. Temperature also has an effect on the concentration levels of air pollutants (Barmpadimos et al., 2011). Air quality and temperature are also affected by other sources (season, time of day, wind) than just green roofs (land use), however all these factors are considered the same across both scenarios.

3.2 Assessing the air quality and temperature health impacts of green roofs

To assess the air quality and temperature health impacts of green roofs, two different methodologies were used. Therefore, this section has two sub-sections, the first focusing on air quality health impacts (Section 3.2.1) and the second focusing on temperature health impacts (Section 3.2.2). The relationship between input and output data and how these determine health impacts is shown in Figure 23.

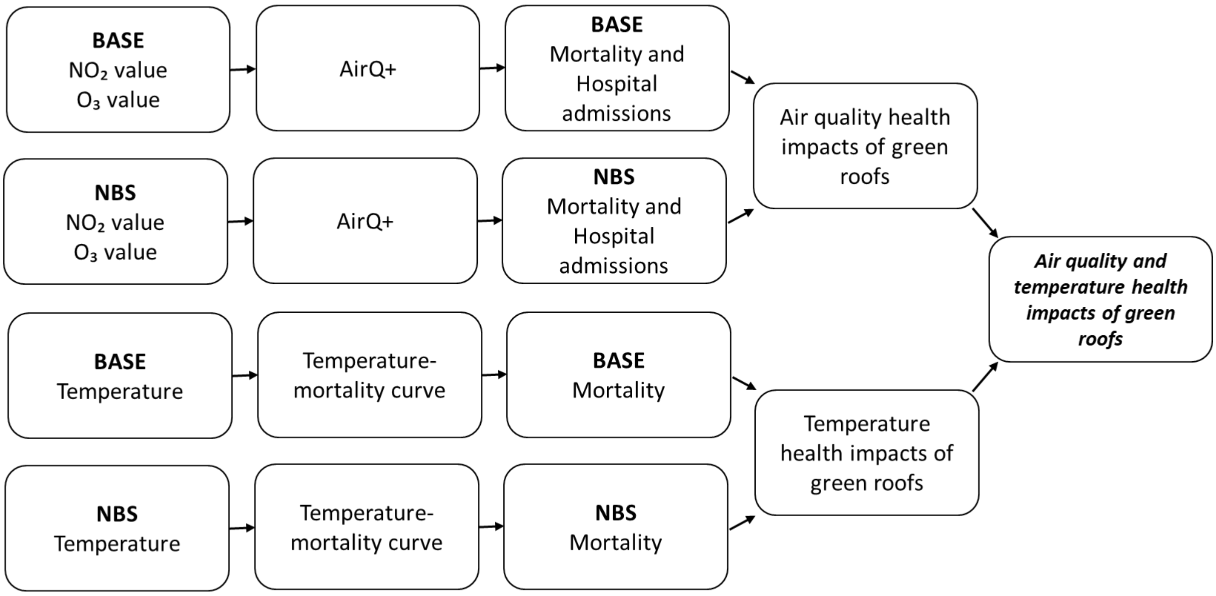

Figure 23. Air quality and temperature health impacts of green roofs flow diagram.

3.2.1 Air quality health impacts of green roofs

The air quality health impacts of green roofs were assessed using AirQ+, which is a tool created by the World Health Organization (WHO). It aims to quantify the health risks associated with short- and long-term exposure to air pollution, through a dose response (WHO, 2021a). The tool and manuals with instructions can be downloaded from the WHO's website: https://www.euro.who.int/en/health-topics/environment-and-health/air-quality/activities/airq-software-tool-for-health-risk-assessment-of-air-pollution.

One of the analyses that AirQ+ runs is an impact assessment that determines the number of health endpoint cases associated with ambient air pollutants. Each pollutant has a range of specific health endpoints in terms of mortality and morbidity (hospital admissions) types. To assess the air quality health impacts of green roofs, four impact assessments were conducted: NO_2 BASE scenario, NO_2 NBS scenario, O_3 BASE scenario and O_3 NBS scenario. Each impact assessment required two sets of input data: for air quality and for incidence/population.

Air quality input data:

- Area

  A multiple area analysis was conducted because each grid cell had unique values of air pollutant concentrations, therefore an area data point was required to distinguish between each grid cell. Although each grid cell had a geographical coordinate (longitude and latitude), for simplicity a single number was allocated to each grid cell that was used as an area identifier.

- Minimum value

  The results (output data) from the previous section (Section 3.1) provided air quality concentration values for a representative week (28th July to 3rd of August, 2013). For NO_2 it was absolute hourly values and for O_3 it was absolute 8-hour values. For each grid cell, the minimum value across that week was selected.

- Maximum value

  The results (output data) from the previous section (Section 3.1) provided air quality concentration values for a representative week (28th July to 3rd of August, 2013). For NO_2 it was absolute hourly values and for O_3 it was absolute 8-hour values. For each grid cell, the maximum value across that week was selected.

- Number of days

  AirQ+ has three options; daily, annual or custom. Therefore, this data point was 7 for all grid cells to indicate that all values were aggregated from an observation of a single week.

Incidence/population input data:

- Area

  The same identifier number for each grid cell as for the air quality input data was used.

- Population at risk

  This is the number of people that will be affected by the air pollutant. Therefore, the annual population residing within each grid cell was identified.

- Incidence

  This is the annual number of incidents that have occurred for each health endpoint of the impact assessment per 100 000 population. Table 2 provides an overview of the incidence data that was used, thereby noting that these are not grid cell specific and some incidences are for the whole of Italy due to availability.

Table 2. Annual incidence per 100 000 population per health endpoint as input data for AirQ+.

Health endpoint	Annual incidence	Location, year	Reference
NO_2			
Mortality, all (natural) causes	2 016.32	Genova, 2013	(I.Stat, 2021)
O_3			
Mortality, all (natural) causes	2 016.32	Genova, 2013	(I.Stat, 2021)
Mortality, respiratory diseases	27.58	Italy, 2013	(WHO, 2020)
Mortality, cardiovascular diseases	149.21	Italy, 2013	(WHO, 2020)
Hospital admissions, respiratory diseases	1 037.36	Italy, 2009	(WHO, 2020)
Hospital admissions, cardiovascular diseases	2 120.11	Italy, 2009	(WHO, 2020)

It should be noted that the output data from AirQ+ is representing an annual estimated number of cases under the assumption that the conditions of the representative week (28th July to 3rd of August, 2013) occur all year round.

The output data from AirQ+, in terms of the annual estimated number of cases attributable to exposure (aggregated across all grid cells) per each health endpoint, was divided by 52 (the number of weeks within a year) to obtain the weekly estimated number of cases attributable to exposure per each health endpoint. This was used as input data for assessing the Health benefits of green roofs (see Section 3.3.2).

3.2.2 Temperature health impacts of green roofs

The temperature health impacts of green roofs were assessed using a temperature-mortality curve. The temperature-mortality curve used has been calculated by Gasparrini et al. (2015) and aims to identify the excess mortality due to temperatures deviating from a temperature threshold (sometimes referred to as a minimum mortality temperature). This curve plots the relative risk (RR) of mortality against temperature. At the temperature threshold, there is no excess mortality due to temperature ($RR = 1$). It should be noted that excess mortality occurs when temperature is higher as well as lower than this threshold. However, for the purpose of this research, the focus is on higher temperatures: heatwave mortality (HWM). Temperature thresholds and the temperature-mortality curve differ per location. For Genova, the temperature threshold is 22.4°C and the temperature-mortality curve is shown in Figure 24, based on data from the 1st of January, 1999 to the 31st of December, 2007 (Gasparrini et al., 2015).

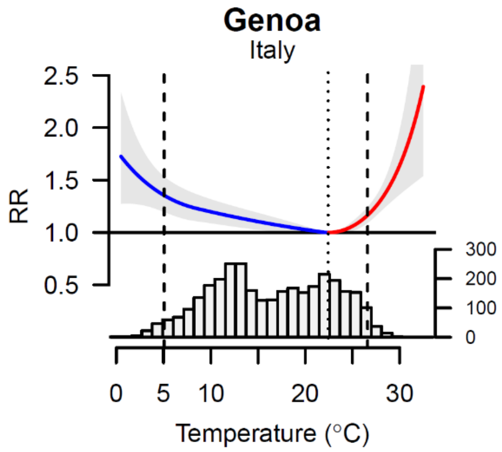

Figure 24. Temperature-mortality curve of Genova, Italy (source: Gasparrini et al., 2015)

To estimate the annual number of excess mortality cases attributable to heatwaves, the following calculation was made twice for each grid cell, representing the BASE scenario and NBS scenario:

Equation 1.

$$\sum_i HWM_i = POP_i \times MR \times (RR_i - 1)$$

in which HWM is the excess mortality cases attributable to heatwaves per grid cell i; POP is the population residing within grid cell i; MR is the annual mortality rate, which for Genova in 2013 (thus, every grid cell) was 13.8 per thousand inhabitant (I.Stat, 2021); and RR is the relative risk of mortality based on the mean temperature within grid cell i. The mean temperature used was from the results (output data) of the previous section (Section 3.1), it is the mean temperature over a representative week (28th July to 3rd of August, 2013). Equation 1 has been adapted from Guo et al. (2018), where an additional component of the number of future heatwave days is used to compare climate change scenarios.

It should be noted that the output data from Equation 1 represent an annual estimated number of heatwave mortality cases under the assumption that the conditions of the representative week (28th July to 3rd of August, 2013) occur all year round.

The output data from Equation 1, in terms of the annual estimated number of excess mortality cases attributable to heatwaves, was aggregated across all grid cells and then divided by 52 (the number of weeks within a year) to obtain the weekly estimated number of excess mortality cases attributable to heatwaves. This was used as input data for assessing the Health benefits of green roofs (see Section 3.3.2).

3.3 Assessing the investment and maintenance costs and health benefits of green roofs

To determine the investment and maintenance costs and health benefits of green roofs, value transfer techniques were used. The costs and benefits have different input data; therefore, this research question was answered by two sub-questions. The first focusing on the costs of implementing (investment) and maintaining green roofs (based on Mačiulytė et al., 2018) and the second focusing on the health benefits or in other words the costs avoided by decreasing health endpoint cases (based on Section 3.2). The relation between input and output data and how these determine costs and benefits is shown in Figure 25.

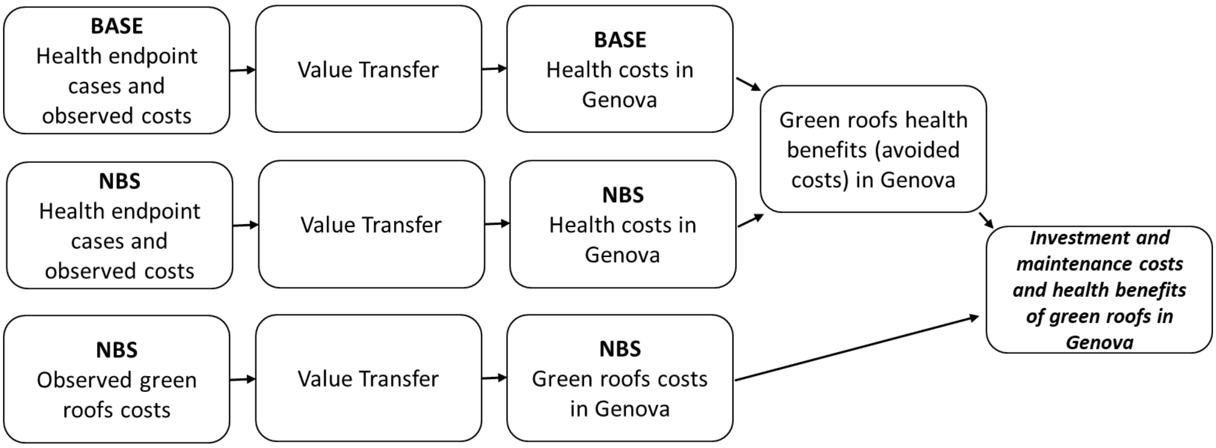

Figure 25. Investment and maintenance costs and health benefits of green roofs flow diagram.

Value transfer is an economic valuation tool that assigns the values estimated at one location to another location. Research is conducted at a study site and then the fixed results are simply transferred to the context of different (policy) site in order to save time and funding from conducting the same research (Alves et al., 2009; Bergstrom & De Civita, 1999; Brouwer, 2000). In this research, the costs of investing and maintaining green roofs as well as the costs of the health endpoints are directly transferred from previous studies without amendments.

3.3.1 Investment and maintenance costs of green roofs

The costs of existing green roofs can be calculated and transferred to situations where green roofs are yet to be implemented. A value transfer takes the results from a study site (previous studies) and, without amendments, directly transfers the estimated values to the context of the policy site (this research; Alves et al., 2009; Bergstrom & De Civita, 1999; Brouwer, 2000). Input data was derived from the UNaLab deliverable “Business Models & Financing Strategies” (Mačiulytė et al., 2018); refer to Table 3. Through research and development, data on the costs of existing green roofs was gathered. The costs considered were both the investment (planning, material and installation, possible roof reinforcements) and maintenance costs. All costs are per square meter and therefore are easily calculated (transferred) to green roofs of any size. For this research, this means multiplying the costs to cover the area of two grid cells (2km² total) that represent green roofs within the NBS scenario. In addition, to be comparable with health benefits, the annual costs were calculated:

Equation 2.

$$C_t = \frac{\sum_a I_{a,0}}{L} + M_t$$

in which C_t are the annual green roof costs in year t; $I_{a,0}$ are the initial investment costs of activity a; L is the lifespan of green roofs, which was assumed to be 50 years (Bianchini & Hewage, 2012); and M_t are the annual maintenance costs in year t.

Table 3. Observed green roof costs for different activities (source: Mačiulytė et al., 2018) *and the annual costs when the lifespan of green roofs is 50 years.*

Activity		**Observed costs**	**Annual costs**
Investment	Planning	20 €/m²	0.4 €/m²/year
	Material and installation	100 - 200 €/m²	2 - 4 €/m²/year
	Roof reinforcement	123 €/m²	2.46 €/m²/year
Maintenance		3 - 12 €/m²/year	3 - 12 €/m²/year
Total		-	7.86 - 18.86 €/m²/year

The output data from Equation 2, in terms of estimated annual activity costs of green roofs was aggregated across all activities (investment and maintenance) and used as input data for Assessing the economic viability of green roofs in Genova (see Section 3.4).

3.3.2 Health benefits of green roofs

The costs of health endpoints can be calculated and transferred to potential cases. A value transfer takes the results from a study site (previous studies) and, without amendments, directly transfers the estimated values to the context of the policy site (this research; Alves et al., 2009; Bergstrom & De Civita, 1999; Brouwer, 2000). For this research, two input data sets are required for this value transfer. The first input data set was derived from previous studies (Holland, 2014); refer to Table 4. Each health endpoint (mortality and hospital admission) has estimated observed costs (see Section 2.2). The second input data set is the number of health endpoint cases. The results (output data) from Section 3.2 were used. To assess the total health benefits of green roofs the following calculation was made:

Equation 3.

$$B = \sum_{e,i} C_e \times (N(BASE)_{e,i} - N(NBS)_{e,i})$$

in which B are the total benefits of green roofs; C_e are the estimated observed costs per health endpoint e; $N(BASE)_{e,i}$ are the number of health endpoint cases in the baseline (BASE) scenario per health endpoint e and per grid cell i; and $N(NBS)_{e,i}$ are the number of health endpoint cases in the green roof (NBS) scenario per health endpoint e and per grid cell i. The difference between the health endpoint cases in the BASE scenario from the health endpoint cases in the NBS scenario ($BASE - NBS$) is also the avoided health endpoint cases due to the implementation of green roofs.

Table 4. Observed health costs for different health endpoints (in 2013 €; source: Holland, 2014).

Health endpoint	Observed costs
NO_2	
Mortality, all (natural) causes	1.28 - 2.62 M€/death
O_3	
Mortality, all (natural) causes	1.28 - 2.62 M€/death
Mortality, respiratory diseases	1.28 - 2.62 M€/death
Mortality, cardiovascular diseases	1.28 - 2.62 M€/death
Hospital admissions, respiratory diseases	2.62 k€/hospital admission
Hospital admissions, cardiovascular diseases	2.62 k€/hospital admission
Temperature	
Mortality, heatwave	1.28 - 2.62 M€/death

The output data from Equation 3, in terms of total health benefits of the representative week, was used as input data for Assessing the economic viability of green roofs in Genova (see Section 3.4).

3.4 Assessing the economic viability of green roofs in Genova

To assess the economic viability of green roofs in Genova, a cost-benefit analysis was performed where the costs consist of the investment and maintenance costs of green roofs and the benefits consist of the costs of health endpoint cases that have been avoided due to green roofs. The relationship between input and output data is shown in Figure 26. This research question answers the objective of this research.

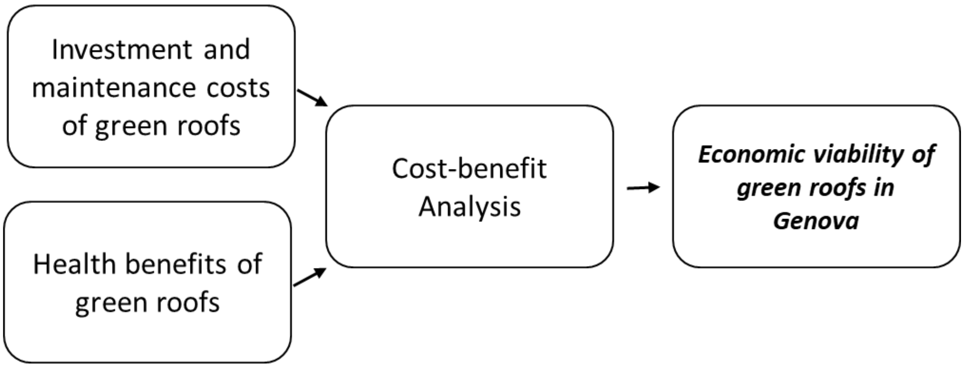

Figure 26. Investment and maintenance costs and health benefits analysis of green roofs flow diagram.

A cost-benefit analysis determines if the costs are higher than the benefits or if the benefits are higher than the costs. A cost-benefit analysis provides cost-benefit indicators, which includes the benefit-cost ratio (BCR; Equation 4) and the net present value (NPV; Equation 5) (Boardman et al., 2018):

Equation 4.

$$BCR = \frac{PV(B)}{PV(C)} = \frac{\sum_{t=0}^{n} \frac{B_t}{(1+s)^t}}{\sum_{t=0}^{n} \frac{C_t}{(1+s)^t}}$$

Equation 5.

$$NPV = PV(B) - PV(C) = \sum_{t=0}^{n} \frac{B_t}{(1+s)^t} - \sum_{t=0}^{n} \frac{C_t}{(1+s)^t}$$

in which $PV(B)$ is the present value benefits; $PV(C)$ is the present value of costs; n is the lifespan of green roofs in years; B_t are the social benefits in year t; C_t are the social costs in year t; and s is the social discount rate.

The input data of investment and maintenance costs was taken directly from Section 3.3. The input data of health benefits was also taken from Section 3.3, however it should be noted that the conditions of the representative summer week (28th July to 3rd of August, 2013), which was used for the health benefit calculations, do not occur all year round. It was assumed that only 12 weeks within a single year (52 weeks) have similar conditions to the representative week; 2 weeks in June, 4 weeks in July, 4 weeks in August and 2 weeks in September (Time and Date, 2021). Therefore, the output data from Equation 3, in terms of total health benefits of the representative week, were multiplied by 12 in order to be considered for a cost-benefit analysis with the annual investment and maintenance costs of green roofs.

The establishment of the green roofs is considered economically viable when the investment and maintenance costs are lower than the health benefits. This means that BCR is greater than 1 and NPV is positive.

Chapter 4. Results

In this chapter the results are described. In Section 4.1, the results are described in terms of putting the values into context within the Baseline scenario (BASE). The following sections describe the results of the Impacts of green roofs on outdoor air quality and temperature (see Section 4.2), the results of the Air quality and temperature health impacts of green roofs (see Section 4.3), the results of the Investment and maintenance costs and health benefits of green roofs (see Section 4.4) and, finally, the results of the Economic viability of green roofs in Genova (see Section 4.5).

4.1 Baseline scenario

This section puts the values of the results into context within the baseline scenario (BASE). The location of the green roofs has been selected by UNaLab together with the residents of Genova and other stakeholders. Their location is marked in green in Figure 27 together with the population distribution. This highlights that the location of the green roofs is in a highly populated residential area.

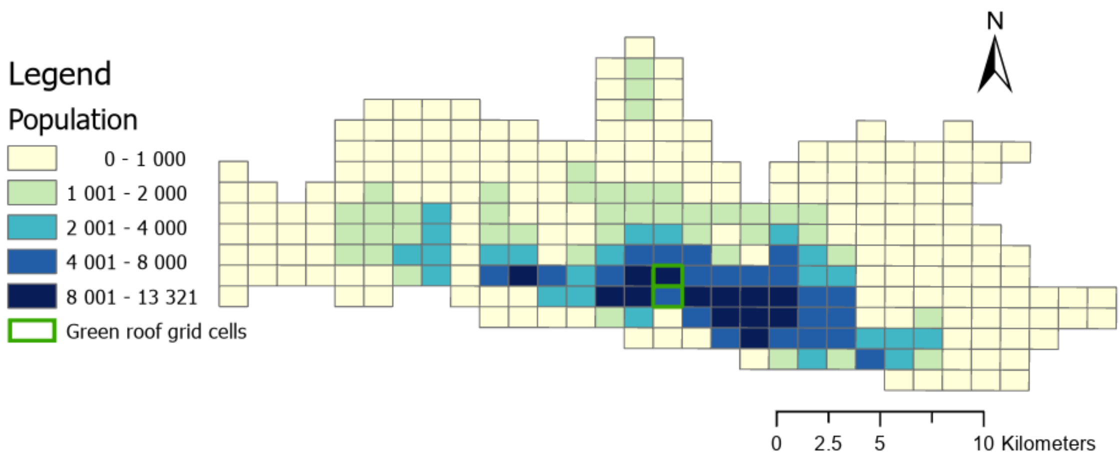

Figure 27. Map of the population distribution in Genova in 2013; green roofs highlighted in green.

The WHO and the European Commission (EC) have both set air pollutant concentration values that, if exceeded, will harm human health (see Table 5). The WHO guideline values are stern and lower than those of the EC. This may be due to the WHO guidelines being updated in 2021 and the EU standards dating back to 2008 (Directive 2008/50/EC). Furthermore, the EC allows for O_3 concentrations to be exceeded for 25 days over 3 years. For NO_2, the representative week (28th July to 3rd of August, 2013) mean values within each grid cell were compared with the WHO guidelines and the EU standards. It was found that 78 grid cells (27.7%) exceeded the WHO guidelines, while only 16 grid cells (5.7%)

exceeded the EU standard. For O_3, the 8-hour maximums across the representative week (28th July to 3rd of August, 2013) within each grid cell, it was found that 276 grid cells (97.9%) exceeded the WHO guidelines, while only 6 grid cells (2.1%) exceeded the EU standard (see Table 5).

Table 5. Air pollutant concentrations values under the WHO guidelines and EC standards, with the number of grid cells in Genova exceeding those values in the representative week (28th July to 3rd August, 2013).

Air Pollutant	Averaging period	WHO (2021b) Guidelines	Grid cells exceeding guidelines	EC (2021a) Standards	Grid cells exceeding standards
Nitrogen dioxide (NO_2)	24-hour mean	25 µg/m³	27.7% (78) *	50 µg/m³	5.7% (16) *
Ozone (O_3)	8-hour daily maximum	100 µg/m³	97.9% (276) **	120 µg/m³ ***	2.1% (6) **

* 168-hour (weekly) mean

** 8-hour weekly maximum

*** With a permitted exceedance of 25 days averaged over 3 years.

Gasparrini et al. (2015) found that the temperature threshold for Genova is 22.4°C and any deviations from this threshold may harm the health of residents. Considering mean temperatures across the representative week, 254 (90.1%) grid cells exceeded this temperature threshold (see Table 6).

Table 6. Temperature threshold for Genova, with the number of grid cells in Genova exceeding that threshold in the representative week (28th July to 3rd August, 2013).

Temperature threshold (Gasparrini et al., 2015)	Grid cells exceeding threshold
22.4°C	90.1% (254)

The WRF-Chem model has calculated the BASE scenario air quality values for NO_2 (Table 7) and O_3 (Table 8), and for temperature (Table 9). For NO_2, the averaging periods of the WHO guidelines and EC standards are a 1-year mean and a 24-hour mean. The results that UNaLab has calculated using WRF-Chem provide a 1-week mean. The average reading of the mean NO_2 value is 21.10 µg/m³, which does not exceed the WHO guidelines for a 24-hour mean. For O_3, the averaging period for the WHO guidelines and EC standards is the daily maximum of the 8-hour measurements. The results that UNaLab has calculated using WRF-Chem provide a 1-week maximum. The average reading of the maximum O_3 value is

111.47 μg/m³, which exceeds the WHO guidelines for an 8-hour daily maximum. For temperature, the temperature threshold is 22.4°C (Gasparrini et al., 2015). The results that UNaLab has calculated using WRF-Chem provide a 1-week mean. The average reading of the mean temperature value is 24.53°C, which exceeds the temperature threshold.

Table 7. WRF-Chem results showing NO_2 values for the representative week (28th July to 3rd August, 2013) in the BASE scenario; the highest, lowest and average readings of maximum, minimum and mean values across all grid cells in Genova.

NO_2	Maximum (μg/m³)	Minimum (μg/m³)	Mean (μg/m³)
Highest reading	593.81	5.08	80.26
Lowest reading	8.10	0.05	2.88
Average reading	116.08	1.01	21.10

Table 8. WRF-Chem results showing O_3 values for the representative week (28th July to 3rd August, 2013) in the BASE scenario; the highest, lowest and average readings of maximum, minimum and mean values across all grid cells in Genova.

O_3	Maximum (μg/m³)	Minimum (μg/m³)	Mean (μg/m³)
Highest reading	123.40	15.63	71.95
Lowest reading	97.50	10.41	65.93
Average reading	111.47	13.54	68.28

Table 9. WRF-Chem results showing temperature values for the representative week (28th July to 3rd August, 2013) in the BASE scenario; the highest, lowest and average readings of maximum, minimum and mean values across all grid cells in Genova.

Temperature	Maximum (°C)	Minimum (°C)	Mean (°C)
Highest reading	34.12	22.27	27.33
Lowest reading	26.94	11.35	21.03
Average reading	31.77	17.83	24.53

Figure 28 shows a map of the NO_2 mean values, Figure 29 shows a map of the O_3 maximum values and Figure 30 shows a map of the temperature mean values.

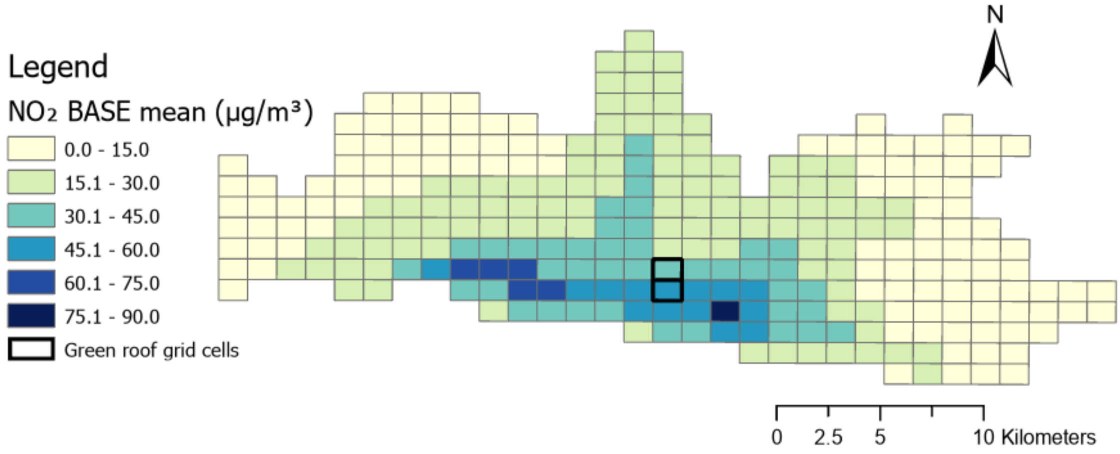

Figure 28. Map of the NO_2 mean for the representative week (28th July to 3rd August, 2013) in the BASE scenario; green roof grid cells highlighted in bold.

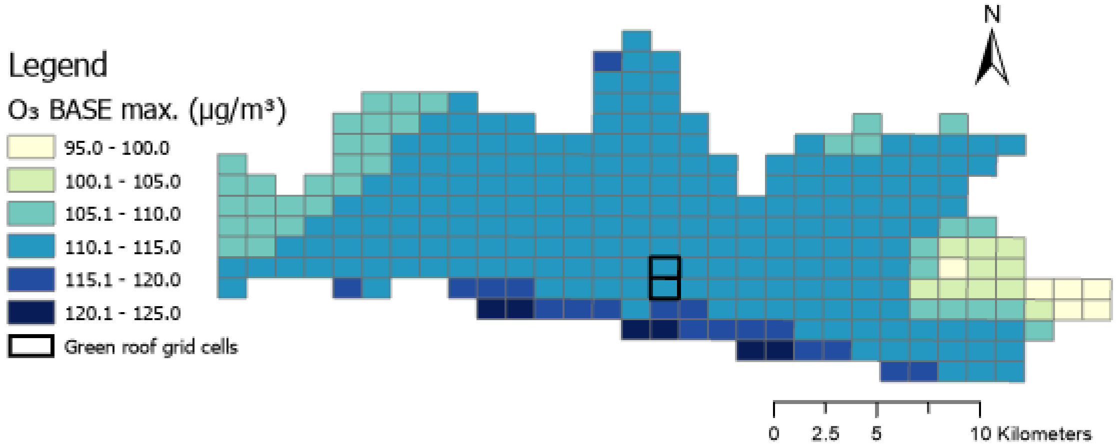

Figure 29. Map of the O_3 maximum for the representative week (28th July to 3rd August, 2013) in the BASE scenario; green roof grid cells highlighted in bold.

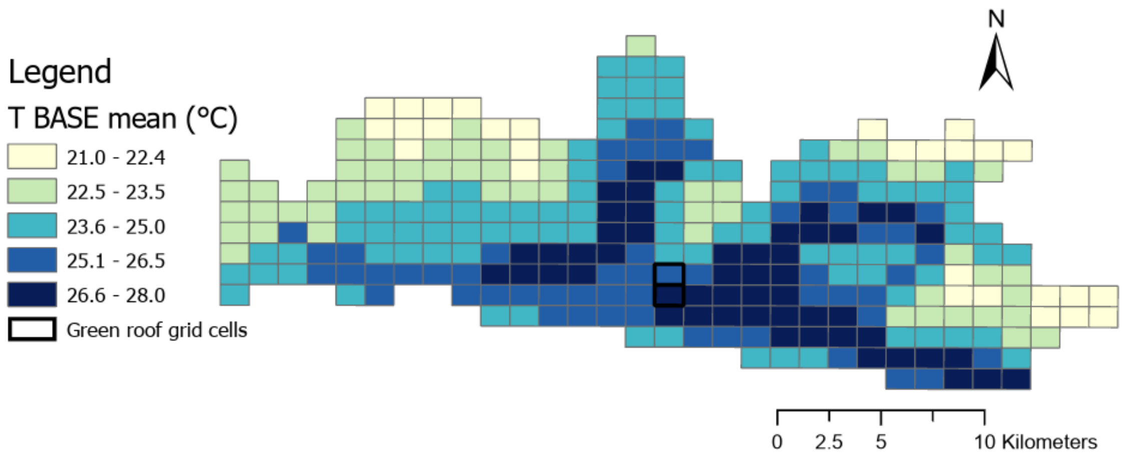

Figure 30. Map of the temperature mean for the representative week (28th July to 3rd August, 2013) in the BASE scenario; green roof grid cells highlighted in bold.

AirQ+ has calculated the BASE scenario health impacts related to air quality (NO_2 and O_3) for the representative week, and temperature-mortality curve was used to calculate the BASE scenario health impacts related to temperature for the representative week. Table 10 shows the BASE scenario results within the representative week (28th July to 3rd August, 2013). The estimated number of mortality cases attributable to NO_2 exposure is 4.37, the estimated number of all mortality cases attributable to O_3 exposure is 3.12, and the estimated number of mortality cases attributable to heatwaves (extreme heat) is 16.17. In addition, the estimated number of hospital admissions due to O_3 exposure is 12.26.

Table 10. AirQ+ and temperature-mortality curve results showing the number of health endpoint cases at BASE scenario of the representative week (28th July to 3rd August, 2013) across all grid cells in Genova.

Health endpoint	Number of cases
NO_2	
Mortality, all	4.37
O_3	
Mortality, all	3.12
Mortality, respiratory	0.05
Mortality, cardiovascular	0.38
Hospital, respiratory	2.42
Hospital, cardiovascular	9.84
Temperature	
Mortality, heatwave	16.17
Total	
Mortality, all causes	23.66
Hospital, all causes	12.26

Value transfer was used to calculate the BASE scenario health endpoint costs (see Table 4) related to the number of health endpoint cases (see Table 10) for the representative week. Table 11 shows the BASE scenario results within the representative week (28th July to 3rd August, 2013). The costs of all the health endpoints (total mortality, all and total hospital, all) are expected to be, on average, about 46.2 M€ within the representative week. From this, NO_2 health endpoint costs comprise ~8.5 M€, O_3 health endpoints costs comprise ~6.1 M€ (6.1 M€ for mortality, all and 32.1 k€ for hospital, all), and temperature health endpoint costs comprise ~31.5 M€.

Table 11. Value transfer results showing the health endpoint costs at BASE scenario of the representative week (28th July to 3rd August, 2013) across all grid cells in Genova.

Health endpoint	Costs
NO_2	
Mortality, all	5.6 - 11.5 M€
O_3	
Mortality, all	4.0 - 8.2 M€
Mortality, respiratory	69.4 - 142.1 k€
Mortality, cardiovascular	0.5 - 1.0 M€
Hospital, respiratory	6.3 k€
Hospital, cardiovascular	25.7 k€
Temperature	
Mortality, heatwave	20.7 - 42.4 M€
Total	
Mortality, all causes	30.3 - 62.0 M€
Hospital, all causes	32.1 k€
Total, all causes	30.3 - 62.0 M€

4.2 Impacts of green roofs on outdoor air quality and temperature

This section answers the first specific research question:

What are the impacts of green roofs on outdoor air quality and temperature?

The output data from WRF-Chem was provided by UNaLab. The maximum, minimum and mean values for both air pollutants (NO_2 and O_3) and temperature are for a representative week (28th July to 3rd of August, 2013). All 282 grid cells (1km^2 covering Genova) have these values for both scenarios (baseline: BASE, and green roofs: NBS). The difference between scenarios is calculated as following:

Equation 6.

$$D = BASE - NBS$$

in which D is the difference between the scenarios; $BASE$ is the value of the baseline scenario; and NBS is the value of the NBS (green roofs) scenario.

For the Impacts of green roofs on nitrogen dioxide (NO_2) see Section 4.2.1, for the Impacts of green roofs on ozone (O_3) see Section 4.2.2, and for the Impacts of green roofs on temperature see Section 4.2.3.

4.2.1 Impacts of green roofs on nitrogen dioxide (NO_2)

The maximum, minimum and mean NO_2 concentration values of the representative week are given in micrograms per cubic meter (µg/m³; hourly). Results in Table 12 show that the NBS scenario NO_2 values are lower than the BASE scenario values (with the exception of the average reading of the minimum value). Within the green roof grid cell #655, the mean value of NO_2 has decreased by 1.24 µg/m³ (-2.4%) and within the green roof grid cell #695, the mean value of NO_2 has decreased by 0.22 µg/m³ (-0.66%). The difference between the average readings of the mean values for the two scenarios across all grid cells, thus the average reduction in mean NO_2 concentrations due to green roofs, is 0.13 µg/m3 (-0.62%). Figure 31 shows a map of the differences between the mean NO_2 values of the two scenarios. The location of the two green roof grid cells (#655 on bottom and #695 on top) are highlighted in bold green. It can be seen that the NO_2 values in surrounding grid cells have also been affected.

Table 12. WRF-Chem results showing the impacts of green roofs on NO_2 concentrations for the representative week (28th July to 3rd August, 2013) in the BASE and NBS scenarios; the highest, lowest and average readings of maximum, minimum and mean values across all grid cells in Genova.

NO_2	Maximum (µg/m³)		Minimum (µg/m³)		Mean (µg/m³)	
Scenario	**BASE**	**NBS**	**BASE**	**NBS**	**BASE**	**NBS**
Highest reading	593.81	583.16	5.08	4.69	80.26	80.04
Lowest reading	8.10	7.90	0.05	0.04	2.88	2.82
Average reading	116.08	115.77	1.01	1.03	21.10	20.97
Green Roof Grid Cell #655	254.35	232.57	1.57	1.39	51.63	50.39
Green Roof Grid Cell #695	116.07	114.50	1.73	1.72	33.33	33.11

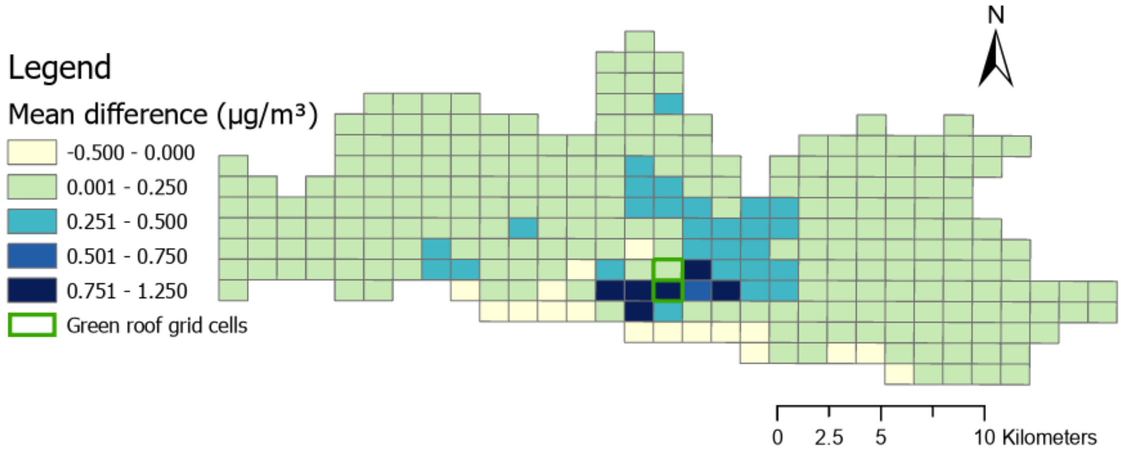

Figure 31. Map of the NO_2 mean difference for the representative week (28th July to 3rd August, 2013) between the BASE and NBS scenarios; green roof grid cells highlighted in bold green.

4.2.2 Impacts of green roofs on ozone (O_3)

The maximum, minimum and mean O_3 concentration values of the representative week are given in micrograms per cubic meter (µg/m³; 8-hourly). Results in Table 13 show that the NBS scenario O_3 values are lower than the BASE scenario values (with the exception of the highest and average reading of the minimum value). Within the green roof grid cell #655, the mean value of O_3 has decreased by 0.26 µg/m³ (-0.39%) and within the green roof grid cell #695, the mean value of O_3 has decreased by 0.29 µg/m³ (-0.42%). The difference between the average readings of the mean values for the two scenarios across all grid cells, thus the average reduction in mean O_3 concentrations due to green roofs, is 0.58 µg/m3 (-0.85%). Figure 32 shows a map of the differences between the mean O_3 values of the two scenarios. The location of the two green roof grid cells (#655 on bottom and #695 on top) are highlighted in bold green. It can be seen that the O_3 values in surrounding grid cells have also been affected.

Table 13. WRF-Chem results showing the impacts of green roofs on O_3 concentrations for the representative week (28th July to 3rd August, 2013) in the BASE and NBS scenarios; the highest, lowest and average readings of maximum, minimum and mean values across all grid cells in Genova.

O_3	Maximum (μg/m³)		Minimum (μg/m³)		Mean (μg/m³)	
Scenario	**BASE**	**NBS**	**BASE**	**NBS**	**BASE**	**NBS**
Highest reading	123.40	114.19	15.63	15.93	71.95	71.06
Lowest reading	97.50	86.81	10.41	10.13	65.93	65.50
Average reading	111.47	94.99	13.54	13.66	68.28	67.70
Green Roof Grid Cell #655	111.04	100.62	14.77	14.85	67.44	67.18
Green Roof Grid Cell #695	110.94	95.10	14.79	14.71	68.34	68.05

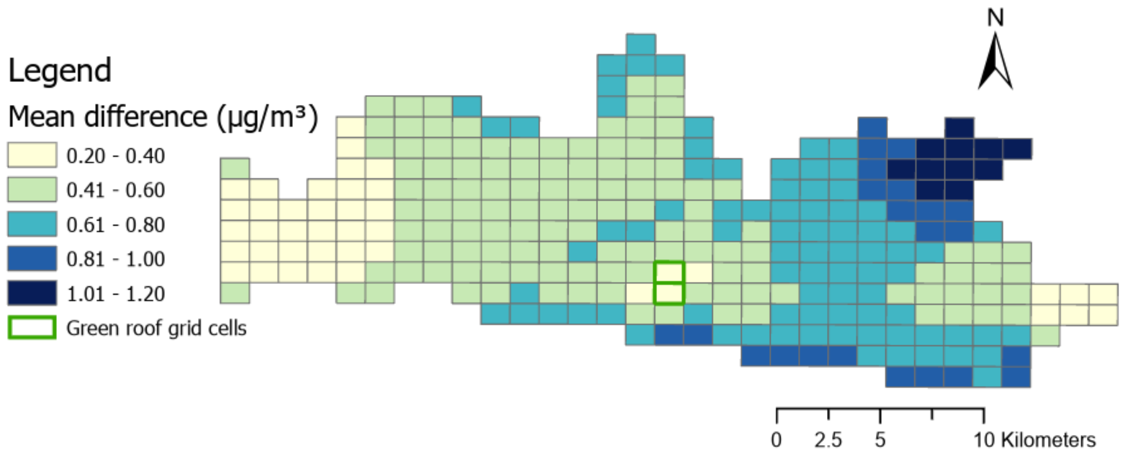

Figure 32. Map of the O_3 mean difference for the representative week (28th July to 3rd August, 2013) between the BASE and NBS scenarios; green roof grid cells highlighted in bold green.

4.2.3 Impacts of green roofs on temperature

The maximum, minimum and mean temperature values of the representative week are given in degrees Celsius (°C; hourly). Results in Table 14 show that there are slight differences between the BASE scenario temperature values and the NBS scenario temperature values. Within the green roof grid cell #655, the mean value of temperature has decreased by 1.07°C (-4.02%) and within the green roof grid cell #695, the mean value of temperature has decreased by 1.73°C (-6.65%). The difference between the average readings of the mean values for the two scenarios across all grid cells, thus the average reduction in mean temperature due to green roofs, is 0.01°C (-0.04%). Figure 33 shows a map of the differences between the mean temperatures of the two scenarios. The location of the two green roof grid cells (#655 on bottom and #695 on top) are highlighted in bold green. It can be seen that the temperature values in the surrounding grid cells have been affected only very slightly.

Table 14. WRF-Chem results showing the impacts of green roofs on temperature for the representative week (28th July to 3rd August, 2013) in the BASE and NBS scenarios; the highest, lowest and average readings of maximum, minimum and mean values across all grid cells in Genova.

Temperature	Maximum (°C)		Minimum (°C)		Mean (°C)	
Scenario	**BASE**	**NBS**	**BASE**	**NBS**	**BASE**	**NBS**
Highest reading	34.12	34.11	22.27	22.27	27.33	27.32
Lowest reading	26.94	26.94	11.35	11.36	21.03	21.01
Average reading	31.77	31.77	17.83	17.85	24.53	24.52
Green Roof Grid Cell #655	33.22	33.30	20.39	19.75	26.64	25.57
Green Roof Grid Cell #695	32.94	32.91	19.29	18.71	26.00	24.27

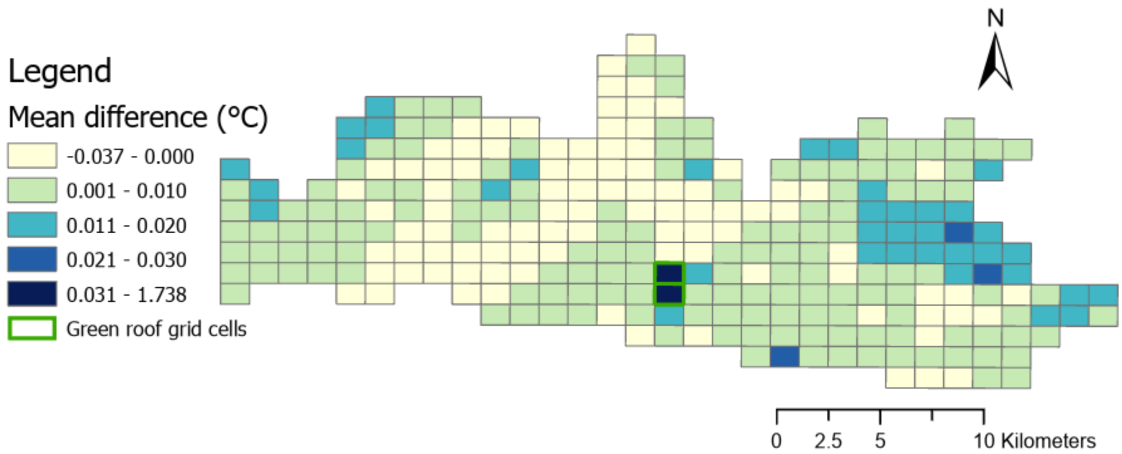

Figure 33. Map of the temperature mean difference for the representative week (28th July to 3rd August, 2013) between the BASE and NBS scenarios; green roof grid cells highlighted in bold green.

4.3 Air quality and temperature health impacts of green roofs

This section answers the second specific research question:

What are the air quality and temperature health impacts of green roofs?

The output data from AirQ+, to assess the Air quality health impacts of green roofs can be seen in Section 4.3.1, and the output data from the temperature-mortality curve, to assess the Temperature health impacts of green roofs can be seen in Section 4.3.2.

4.3.1 Air quality health impacts of green roofs

The output data from AirQ+ is shown in Table 15. These results are for the representative week and are cumulated across all grid cells. NO_2 emissions within the BASE scenario are estimated to attribute to 4.37 deaths and within the NBS scenario to 4.31 deaths. This means that the introduction of green roofs is estimated to prevent 0.06 deaths attributed to NO_2 emissions within the representative week. O_3 emissions within the BASE scenario are estimated to attribute to 3.12 deaths and within the NBS scenario to 2.71 deaths. This means that the introduction of green roofs is estimated to prevent 0.40 deaths attributed to O_3 emissions within the representative week. Furthermore, O_3 emissions within the BASE scenario are estimated to attribute to 2.42 hospital admissions related to respiratory diseases and 9.84 hospital admissions related to cardiovascular diseases. Within the NBS scenario, O_3 emissions are estimated to attribute to 2.11 hospital admissions related to respiratory diseases and 8.58 hospital admissions related to cardiovascular diseases. This means that 0.31 respiratory and 1.26 cardiovascular hospital admissions attributed to O_3 emissions are estimated to be prevented with the introduction of green roofs within the representative week.

Table 15. AirQ+ results showing the air quality (NO_2 and O_3) health impacts for the representative week (28th July to 3rd August, 2013) in the BASE and NBS scenarios across all grid cells in Genova.

Health endpoint	**Estimated number of cases attributable to exposure in the** BASE **scenario**	**Estimated number of cases attributable to exposure in the** NBS **scenario**
	NO_2	
Mortality, all	4.37	4.31
	O_3	
Mortality, all	3.12	2.71
Mortality, Respiratory	0.05	0.05
Mortality, Cardiovascular	0.38	0.33
Hospital, Respiratory	2.42	2.11
Hospital, Cardiovascular	9.84	8.58

4.3.2 Temperature health impacts of green roofs

The output data from the temperature-mortality curve is shown in Table 16. These results are for the representative week and are cumulated across all grid cells. Temperatures above the 22.4°C threshold (heatwave) are estimated to attribute to 16.17 deaths within the BASE scenario and 15.85 deaths within the NBS scenario. This means that the introduction of green roofs is estimated to prevent 0.32 deaths attributed to heatwave excess mortality within the representative week.

Table 16. Temperature-mortality curve results showing the temperature health impacts for the representative week (28th July to 3rd August, 2013) in the BASE and NBS scenarios across all grid cells in Genova.

Health endpoint	Estimated number of cases attributable to exposure in the BASE scenario	Estimated number of cases attributable to exposure in the NBS scenario
Mortality, heatwave	16.17	15.85

4.4 Investment and maintenance costs and health benefits of green roofs

This section answers the third specific research question:

What are the investment and maintenance costs and health benefits of green roofs?

The output data from the value transfer to assess the Investment and maintenance costs of green roofs can be seen in Section 4.4.1, and the output data from the value transfer to assess the Investment and maintenance costs of green roofs

The output data from the value transfer assessing the costs of green roofs is shown in Table 17. The observed annual costs and the observed total costs of green roofs (see Table 3) are multiplied to represent the NBS scenario green roofs that cover two grid cells; 2km² in total. The annual investment and maintenance costs of green roofs are, on average, 26.7 M€/year for the lifespan of 50 years.

Table 17. Value transfer results showing the annual and total investment and maintenance costs of the NBS scenario (green roofs), considering a green roofs lifespan of 50 years.

Activity	Annual NBS costs (M€/year)	Total NBS costs (M€)
Planning	0.8	40
Material and installation	4.0 - 8.0	200 - 400
Roof reinforcement	4.9	246
Maintenance	6.0 - 24.0	300 - 1 200
Total	15.7 - 37.7	786 - 1 886

Health benefits of green roofs can be seen in Section 4.4.1.

4.4.1 Investment and maintenance costs of green roofs

The output data from the value transfer assessing the costs of green roofs is shown in Table 17. The observed annual costs and the observed total costs of green roofs (see Table 3) are multiplied to represent the NBS scenario green roofs that cover two grid cells; 2km² in total. The annual investment and maintenance costs of green roofs are, on average, 26.7 M€/year for the lifespan of 50 years.

Table 17. Value transfer results showing the annual and total investment and maintenance costs of the NBS scenario (green roofs), considering a green roofs lifespan of 50 years.

Activity	Annual NBS costs (M€/year)	Total NBS costs (M€)
Planning	0.8	40
Material and installation	4.0 - 8.0	200 - 400
Roof reinforcement	4.9	246
Maintenance	6.0 - 24.0	300 - 1 200
Total	15.7 - 37.7	786 - 1 886

4.4.2 Health benefits of green roofs

The output data from the value transfer assessing the health benefits of green roofs is shown in Table 18. The estimated observed health endpoint costs (see Table 4) and the estimated number of health endpoint cases (see Section 4.3) are used to calculate the total health benefits based on Equation 3. The total health benefits of green roofs, due to the impact on air quality and temperature, are on average of 1.5 M€ within the representative week.

Table 18. Value transfer results showing the avoided health endpoint cases and the air quality (NO_2 and O_3) and temperature health benefits of green roofs for the representative week (28th July to 3rd August, 2013) across all grid cells in Genova.

Health endpoint	Avoided cases	Health benefits
NO_2		
Mortality, all	0.06	0.1 - 0.2 M€
O_3		
Mortality, all	0.40	0.5 - 1.1 M€
Mortality, Respiratory	0	0 €
Mortality, Cardiovascular	0.05	59 - 121 k€
Hospital, Respiratory	0.31	0.8 k€
Hospital, Cardiovascular	1.26	3.3 k€

Temperature		
Mortality, heatwave	0.32	0.4 - 0.8 M€
Total		
Mortality, all causes	0.79	1.0 - 2.1 M€
Hospital, all causes	1.57	4.1 k€
Total, all causes	-	1.0 - 2.1 M€

4.5 Economic viability of green roofs in Genova

This section answers the fourth and last specific research question:

What is the economic viability of implementing green roofs in Genova, Italy?

For a comparison between the investment and maintenance costs and the health benefits, total annual health benefits were calculated. This is because input data of the investment and maintenance costs of green roofs was annual while the input data of the health benefits was for a representative week. The total Annual health benefits can be seen in Section 4.5.1. The output data from the Cost-benefit analysis to assess the economic viability of green roofs in Genova can be seen in Section 4.5.2.

4.5.1 Annual health benefits

The output data from Section 4.4.2 (Equation 3), in terms of total health benefits for the representative week, were multiplied by 12 to obtain the total annual health benefits. It was assumed that the conditions of the representative week occur for 12 weeks within a year. These total annual health benefits (see Table 19) were used as input data for the cost-benefit analysis (see Section 4.5.2). The total annual health benefits of green roofs, due to the impact on air quality and temperature, are on average 18.5 M€/year.

Table 19. Annual air quality (NO_2 and O_3) and temperature health benefits of green roofs, across all grid cells in Genova.

Health endpoint	Annual health benefits (12 weeks)
NO_2	
Mortality, all	0.9 - 1.9 M€/year
O_3	
Mortality, all	6.2 - 12.7 M€/year
Mortality, Respiratory	0 €/year
Mortality, Cardiovascular	0.7 - 1.5 M€/year
Hospital, Respiratory	9.8 k€/year
Hospital, Cardiovascular	39.5 k€/year

Temperature	
Mortality, heatwave	4.9 - 10.1 M€/year
Total	
Mortality, all causes	12.1 - 24.7 M€/year
Hospital, all causes	49.2 k€/year
Total, all causes	12.1 - 24.8 M€/year

4.5.2 Cost-benefit analysis

The output data from the cost-benefit analysis to assess the economic viability of green roofs in Genova is presented by cost-benefit indicators: the benefit-cost ratio (BCR; Equation 4) shown in Table 21 and the net present value (NPV; Equation 5) shown in Table 22. The input data of the annual investment and maintenance costs (see Section 4.4.1) and the input data of the annual (12 weeks) health benefits (see Section 4.5.1) both have a monetary range. Therefore, a sensitivity analysis is performed for three categories of cost and benefit ranges:

- Low: This category considered the bottom monetary range value.
- Average: This category considered the average monetary range value.
- High: This category considered the upper monetary range value.

Corresponding estimates of the low, average and high monetary values for costs (from Table 17) and benefits (from Table 19) are shown in Table 20.

Table 20. Estimates of the three categories of monetary ranges for annual costs and benefits.

	Costs (M€/year)	Benefits (M€/year)
Low	15.7	12.1
Average	26.7	18.5
High	37.7	24.8

The establishment of the green roofs is considered economically viable when BCR is greater than 1. Therefore, it is annually economically viable when considering the low monetary range of costs and the average or high monetary range of benefits. In all other cases the establishment of green roofs is not economically viable.

Table 21. Cost-benefit sensitivity analysis results showing the annual benefit-cost ratio for three categories of monetary ranges for costs and benefits.

Annual BCR		Costs		
		Low	Average	High
Benefits	Low	0.77	0.45	0.32
	Average	**1.17**	0.69	0.49
	High	**1.58**	0.93	0.66

The establishment of the green roofs is also considered economically viable when NPV is positive. Therefore, it is annually economically viable when considering the low monetary range of costs and the average or high monetary range of benefits. In all other cases the establishment of green roofs is not economically viable.

Table 22. Cost-benefit sensitivity analysis results showing the annual net present value for three categories of monetary ranges of costs and benefits.

Annual NPV (M€/year)		Costs		
		Low	Average	High
Benefits	Low	-3.6	-14.6	-25.6
	Average	**2.7**	-8.3	-19.3
	High	**9.1**	-1.9	-12.9

Chapter 5. Discussion and conclusions

In this chapter the results are discussed and conclusions are made. In Section 5.1, the main findings are summarized and discussed/compared against other publications. In Section 5.2, recommendations (the main message) and limitations are highlighted.

5.1 Summary and discussion

Previous studies have examined the effects of green roofs on air quality, while other studies examined the effects of green roofs on indoor and outdoor temperatures. However, a combination of the two is rarely explored. Furthermore, the costs associated with green roofs have also mainly been studied separately (i.e., either costs or benefits/avoided costs). The objective of this research is **to assess the outdoor air quality and temperature health impacts and benefits from green roofs**, which was done by answering four specific research questions. This research is conducted in the context of the UNaLab project and provides a case study for green roofs in Genova, Italy.

1. What are the impacts of green roofs on outdoor air quality and temperature?

The Weather Research Forecasting model with chemistry (WRF-Chem) was used by UNaLab to assess the impacts of green roofs on outdoor air quality and temperature (see Section 4.2). For air quality, in the baseline (BASE) scenario, the average reading of 1-week mean NO_2 values was 21.10 μg/m³, which does not exceed the WHO guidelines for a 24-hour mean (25 μg/m³; WHO, 2021b). In the BASE scenario, the average reading of 1-week maximum O_3 values was 111.47 μg/m³, which exceeds the WHO guidelines for an 8-hour daily maximum (100 μg/m³; WHO, 2021b). The difference between the average readings of 1-week mean O_3 values for the BASE scenario and the NBS scenario (green roofs) across all grid cells in Genova, thus the average reduction in concentrations due to green roofs for a week, was 0.13 μg/m3 (-0.62%) for NO_2 and 0.58 μg/m3 (-0.85%) for O_3. In particular, grid cells surrounding the two green roof grid cells were affected. Similarly, Currie & Bass (2008) found that within a year NO_2 concentrations can be reduced by 7.01 μg/m³ (0.13 μg/m³ in a week) and O_3 concentrations can be reduced by 13.80 μg/m³ (0.27 μg/m³ in a week).

For temperature, the average reading of 1-week mean temperature values was 24.5°C, which exceeds the temperature threshold of 22.4°C (Gasparrini et al., 2015). The difference between the average readings of 1-week mean temperature values for the BASE scenario and the NBS scenario (green roofs) across all grid cells in Genova, thus the average reduction in mean temperature due to green roofs for a week, was 0.01°C (-0.04%). This is because the temperature in grid cells surrounding the two green roof grid cells were barely affected. When focusing solely on the two green roof grid cells, the mean value of temperature had decreased by 1.07°C (-4.02%) in grid cell #655 and by 1.73°C (-6.65%) in grid cell #695. Similarly, He et al. (2020) found that within summer temperature can be reduced by 0.35°C.

To conclude, considering all grid cells, the largest impact of green roofs was on air quality concentrations, mainly O_3. Ascenso et al. (2021) also found that there was greater impact on air quality than on temperature in the Netherlands. Whereas, Knight et al. (2021) found that the impact on O_3 was not clear.

2. What are the air quality and temperature health impacts of green roofs?

AirQ+ and temperature-mortality curve were used to assess the air quality and temperature health impacts of green roofs (see Section 4.3). In the baseline (BASE) scenario, within the representative week (28th July to 3rd August, 2013), the estimated number of total mortality cases was 23.66; 4.37 (19%) was attributable to NO_2 exposure, 3.12 (13%) was attributable to O_3 exposure, and 16.17 (68%) was attributable to heatwaves (extreme heat temperatures). In addition, the estimated number of hospital admissions due to O_3 exposure is 12.26. The introduction of green roofs was estimated to prevent a total of 0.79 deaths within the week; 0.06 (8%) deaths attributed to NO_2 emissions, 0.40 (51%) deaths attributed to O_3 emissions and 0.32 (41%) deaths attributed to heatwave excess mortality. Furthermore, 1.57 hospital admissions attributed to O_3 emissions were estimated to be prevented. He et al. (2020) found that heatwave mortality rate can be reduced by 0.2% with green roofs, this research found a more significant reduction of almost 2%.

The highest mortality is attributable to heatwaves (temperature), however green roofs prevent the most deaths attributed to O_3 emissions. To conclude, the largest health impact of green roofs was on air quality related health endpoints, mainly O_3. Ballocci (2021) also found that within air quality, green roofs have a higher impact on O_3 health endpoints than on NO_2 health endpoints.

3. What are the investment and maintenance costs and health benefits of green roofs?

Value transfers were used to assess the investment and maintenance costs, and the health benefits of green roofs (see Section 4.4). It was found that the annual investment and maintenance costs of introducing green roofs in the two grid cells (2km^2 total) were, on average, 26.7 M€/year for a green roof lifespan of 50 years; 11.7 M€/year (44%) investment and 15 M€/year (56%) maintenance costs. In the baseline (BASE) scenario, within the representative week (28th July to 3rd August, 2013), the expected costs of all the health endpoints (total mortality, all and total hospital, all) was, on average, 46.2 M€; NO_2 health endpoint costs ~8.5 M€ (19%), O_3 health endpoints cost ~6.1 M€ (13%), and temperature health endpoint costs ~31.5 M€ (68%). The avoided costs due to green roofs in the representative week were, on average, 1.5 M€; 0.1 M€ (7%) NO_2 health benefits, 0.8 M€ (53%) O_3 health benefits, and 0.6 M€ (40%) temperature health benefits. Assuming that the conditions of the representative week occur for 12 weeks within a year, the annual total health benefits of green roofs, due to the impact on air quality (NO_2 and O_3) and temperature, were, on average, 18.5 M€/year.

The highest health endpoint costs are attributable to temperature; however, the highest health benefits (avoided costs) are attributed to O_3. To conclude, the annual average costs of green roofs were 26.7 M€/year, where the highest costs are maintenance costs, and the annual average health benefits were 18.5 M€/year, where the highest benefits are avoided O_3 mortality, all costs. For a similar green roof area, Teotónio et al. (2018) found lower annual costs for an intensive green roof in Lisbon (10.9 M€/year) and higher annual social benefits (25.3 M€/year), primarily due to additional benefits being considered, such as (storm) water retention, noise insulation and ecological preservation.

4. What is the economic viability of implementing green roofs in Genova, Italy?

A cost-benefit analysis was used to assess the economic viability of green roofs in Genova, Italy (see Section 4.5). To conclude, the benefit-cost ratio (BCR) was greater than 1 and the net present value (NPV) was positive when the low (15.7 M€/year) monetary range of costs and the average (18.5 M€/year) or high (24.8 M€/year) monetary range of benefits were considered. Therefore, the establishment of the green roofs was only considered annually economically viable within these cases and in all other cases the establishment of green roofs was not economically viable. Based on the findings of Teotónio et al. (2018), a BCR for green roofs of 2.32 is derived, while Sproul et al. (2014) found that green roofs are not economically viable due to a net saving of -53.4 €/m².

5.2 Recommendations and limitations

5.2.1 Recommendations

From the perspective of a building owner, green roofs are generally not economically viable. This is because all the costs fall upon the owner and the health benefits discussed within this research are mainly societal. For a recommendation, the building owner should look into other benefits (such as water retention, noise insulation, reduced energy consumption, aesthetics, property value)[1] as well as into possibilities of lowering costs (green subsidies)[1].

From the perspective of a local government, green roofs can be economically viable under certain conditions. If the interest of the community, and not simply the interest of the building with the green roof, is considered, then the benefits of green roofs can be spatially distributed. With higher property values due to green roofs, the area may experience gentrification, which may or may not be something that the local government desires. With larger areas more stakeholders are involved and their interest should be discussed and considered. It should be noted that when investment and maintenance costs are of the lower monetary range, both the high and average monetary range of health benefits make green roofs economically viable. Furthermore, local governments may be required to implement NBS as part of international greening policies, which may lead to investment costs being subsidized and, hence, green roofs may become economically viable.

From the perspective of a private sector, green roofs can be economically viable under certain conditions. Owners of a single or multiple buildings can also consider the interests of the community and the spatially distributed benefits. Apart from subsidies, other methods of lowering costs include, for example, optimizing costs of materials and transportation by agreeing to green multiple roofs simultaneously, sharing the costs with other beneficiaries through compensation mechanisms or finding investors.

The following aspects should be considered before making a decision;

- Stakeholders affected
- Distribution and range of costs
- Distribution and range of health benefits
- Possible alternative benefits
- Possible alternative fundings

[1] See, for example, Teotónio et al. (2018)

Future studies may expand and improve on this research. This may be done by improving on the limitations (see Section 5.2.2) as well as exploring certain areas in more depth. An additional area of exploration could be into other benefits from green roofs impacts, or health benefits from other NBS. For example, green roofs impacts stormwater and noise pollution, or combining green roofs with green façade or only painting roofs white for cooling as suggested by Sproul et al. (2014).

5.2.2 Limitations

There are limitations to the models used within this research as well as the input data used and the assumptions made, which can be addressed in future studies.

Models:

The WRF-Chem model applies a dominant land use for the whole grid cell (1km²). This means that the NBS scenario of green roofs covered the entire grid cell, which is not realistic as the grid cell is not a single rooftop. Furthermore, the simulation of a green roof means a grass land use, therefore this no longer considers the impact of the building structure underneath the roof. Currie & Bass (2008) found that a combination of grass, shrubs and trees yields the highest air pollution removal. Rowe (2011) highlights that the choice of plant species is also very important due to different characterises and abilities to absorb pollutants in certain conditions (for example, dormant during winter). These specification details may result in alternative values for green roof impacts and thus, also for health impacts and benefits.

There were some bugs encountered with AirQ+, which meant that spatial data for NO_2 could not be obtained. Similarly, only a short-term impact assessment was made due to the long-term lacking spatial data. Furthermore, due to the impacts representing a single week, values were small and automatic rounding of the model caused discrepancies. Knight et al. (2021) found that impacts of greening may reach up to 1.25km from their implementation. Therefore, more accurate spatial data results would have provided a clearer insight into the direct air quality health impacts.

The temperature-mortality curve equation was calculated from a figure within Gasparrini et al. (2015), therefore it may not be precise. Furthermore, extreme heat temperatures cause dehydration and worsen the conditions of chronic diseases (WHO, 2018b). Therefore, there are multiple other health endpoints related to temperature that have not been calculated.

Value transfer was used without amendments; however, contexts differ and costs of green roofs and health endpoints evolve over time and vary across countries. Furthermore, all costs were direct and/or average costs. For example, the investment and maintenance costs of green roofs are indirectly affected by the accessibility to the site; does the surrounding area allow for manipulation of machinery, does the height of the roof require special machinery, can the materials be stored on-site or do they require long transportation (Mačiulytė et al., 2018). Similarly, green roofs may also provide psychological/mental health benefits.

A cost-benefit analysis produces a simple number that policy makers may base their decisions on; however, it only represents the identified costs and benefits. There are many other factors that should be considered and a cost-benefit analysis should only be used as an orientation guide due to unforeseen events and impacts. In addition, the identified costs generally apply to the building owners, whereas the identified benefits are societal.

Input data:

The air quality (NO_2 and O_3) and temperature data was provided only for a representative week in summer. This data was then used to represent an annual cost-benefit analysis, which may be skewed during winter. For a more accurate representation of the whole year, data for every day across multiple years would be preferred.

The number of health endpoint cases (incidence of mortality and hospital admission) was mostly provided for Italy as a whole, rather than for Genova. The total mortality rate in Italy was used in the equation for heatwave excess mortality although the equation required the non-heatwave mortality rate in Genova. Genova is the 6th largest city in Italy; therefore, it may be expected that the number of cases is higher than the average for the whole of Italy.

The temperature threshold for Genova was provided by Gasparrini et al. (2015), which has been critiqued when compared to other publications. Longden (2019) found that the temperature threshold for Australia should be lower than what Gasparrini et al. (2015) claim. On the other hand, Baccini et al. (2008) found higher temperature thresholds for different cities in Italy; Milan 31.8°C, Rome 30.3°C, Turin 27.0°C. Hence, the temperature threshold for Genova could be reconsidered.

The investment costs of green roofs assumed that roof reinforcement will be required on the entire roof (100%). Sproul et al. (2014) examined the costs of the whole life cycle of green roofs and has identified end of life costs that were not considered within this research: replacement and/or disposal costs. On the other hand, experience with green roofs (in both know-how and technology) and optimization of material use may lead to a decrease in the investment and maintenance costs.

The costs of health endpoints can be rather subjective, as highlighted in Section 2.2. Holland (2014) presented the health endpoint values within the European Union (EU) member states, however these may be outdated. Also, the willingness to pay (WTP) is influenced by numerous factors and may differ across countries even within the EU member states. The health benefits of green roofs are based on these costs and therefore, the use of different cost values will drastically alter the results of this research.

Assumptions:

It was assumed that the lifespan of green roofs is 50 years. Bianchini & Hewage (2012) have found that it can be anywhere from 40 years to 55 years. This means that the annual costs of green roofs may differ due to the investment costs being spread across fewer or more years.

It was also assumed that the conditions of the representative week (28th July to 3rd August, 2013) occur for 12 weeks within a year. This means that only the benefits of the warmest 12 weeks were considered and the remaining 40 weeks of the year were considered neutral. However, it is possible that weeks with average temperatures still result in benefits.

Study boundaries:

NBS provide ecosystem services. Within this research the focus was on an aspect of the regulating services, whereas there are benefits associated with green roofs also in the provisioning and cultural services. A green roof could provide additional benefits when, for example, it is turned into a green roof garden or a green roof farm that provides recreational, spiritual and education services as well as providing provisioning services (food).

In addition to outdoor air quality and temperature, green roofs also affect indoor air quality and temperature. Acting as an insulation layer, green roofs keep the indoors cooler in the summer and warmer in the winter. As a result, there are indirect effects on air quality. For example, due to the decrease in the use of air conditioning, energy consumption is lower for that building and, hence, there are lower emissions from power plants. In addition to the health benefits of lower emissions, a lower energy bill is also a benefit for the residents.

In addition to NO_2 and O_3, there are other air quality pollutants that are impacted by green roofs. These include, for example, particulate matter (PM), sulphur dioxide (SO_2), volatile organic compounds (VOC). The inclusion of these air quality pollutants may increase the health benefits of green roofs further.

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