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Reducing greenhouse gas emissions in communities – evidence and opportunities for change in Aotearoa

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Revision	Details
1	Draft literature review and practice reviews to demonstrate work in progress
2	Additional practice reviews – separate document
3	Full evidence base report

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Glossary and abbreviations

GHG	Greenhouse gas
CO_2	Carbon dioxide
LCA	Life cycle assessment
HIA	Health impact assessment
IPCC	Intergovernmental Panel on Climate Change
Urban form	Physical characteristics that make up the built environment
Co-benefits	Community-level benefits related to mitigation measures to reduce GHG emissions. They include aspects of 'well-functioning' neighbourhood. town and cities such as wellbeing, social cohesion, accessibility, and so on.
Greening	Incorporating nature into urban areas

Disclaimers and Limitations

This report ('**Report**') has been prepared by WSP exclusively for BRANZ ('**Client**') in relation to Reducing Greenhouse Gas Emissions in communities ('**Purpose**') and in accordance with the BRANZ contract reference LR14405 dated 16 December 2021. The findings in this Report are based on and are subject to the assumptions specified in the Report. WSP accepts no liability whatsoever for any reliance on or use of this Report, in whole or in part, for any use or purpose other than the Purpose or any use or reliance on the Report by any third party.

Abstract

Greenhouse gas (GHG) emissions from urban areas are one of the main drivers of climate change. To mitigate the effects of climate change, we need to significantly reduce emissions. The way in which our urban areas are planned, designed, built, and used plays a major role in their impact on the environment. Strategies such as compact development and the utilisation of sustainable building materials can make a big difference. At the same time, the effect of urban environments on outcomes of health and wellbeing has become more widely recognised. Our efforts to mitigate GHG emissions therefore present a unique opportunity to do things differently — how can we incorporate co-benefits for communities in our response?

The following report outlines the development of an evidence base for interventions and changes at neighbourhood-to-city scales that have delivered GHG emissions reduction and co-benefits.

The evidence base comes from a literature review with two main focuses: to understand the pathways that connect urban form, greenhouse gas emissions, and community outcomes; and to identify examples of interventions that have occurred within the scope of these pathways. The aim was to build an evidence base of pathways and interventions that can support urban practitioners in their efforts.

In addition to the literature review, a practice review was conducted. This involved interviews with several practitioners to discuss lessons from the industry for the successful implementation of interventions.

The findings show evidence for several pathways in several different domains — including urban greening, urban design, mobility and transportation, energy, water, and construction and 'smart' technology. Some of these areas are more studied than others — notably, transport and building energy use. Evidence of co-benefits for community health and wellbeing can be found within all domains. The practice reviews highlight the importance of local expert knowledge and an evidence base to support intervention success.

Executive summary

Climate change is one of the most challenging issues we face today. Warmer average temperatures, rising sea levels, more frequent extreme weather events, and a loss of biodiversity are some of the changes we are already seeing. Communities all around the world are being affected by these changes, resulting in people being displaced from their homes, crops failing, and damages to infrastructure.

To mitigate the effects of climate change, we need to significantly reduce emissions. Greenhouse gas (GHG) emissions from urban areas are one of the main drivers of climate change, particularly in developed economies such as New Zealand, where per capita GHG emissions are high. The ways in which our urban areas are planned, designed, built, and used plays a major role in their impact on the environment. At the same time, we are also beginning to better understand how well-functioning built environments contribute to the health and wellbeing of communities.

Our efforts to mitigate GHG emissions in urban areas therefore presents a unique opportunity to do things differently. By considering the co-benefits of GHG emissions reduction interventions, we can both respond to climate change and advance outcomes of health and wellbeing. For example, compact development can support more connected communities by making it easier for people to socialise with each other, as well as access key destinations such as services, amenities, employment, and education without using a car. This can result in GHG emissions savings through fewer vehicle emissions and more energy-efficient buildings, and community co-benefits through outcomes such as greater levels of social resiliency and health improvements due to increased active travel (such as walking and cycling).

The following report outlines our research on urban interventions at neighbourhood-to-city scales that can deliver both GHG emissions reductions and community co-benefits. With efforts to respond to climate change needed now more than ever, we wanted to identify evidence for making the changes required to ensure we reduce emissions *and* have well-functioning neighbourhoods, towns, and cities.

The project aim was to build an evidence base of pathways and interventions that can be used to support urban practitioners in their efforts. Our research involved a literature review with two main focuses: understanding the pathways that connect urban form, GHG emissions, and community outcomes; and identifying examples of interventions that have occurred within the scope of these pathways.

To support the literature review, we also conducted a practice review. This involved interviews with four practitioners who had worked on relevant interventions to identify overarching lessons for their successful implementation and evaluation.

Some of our key findings from these reviews include:

- The literature discusses a range of intervention pathways across six different domains, including urban greening, urban design, mobility and transportation, energy, water, and the use of ‘smart’ construction methods and technologies. Some of these areas are more studied than others — notably, transportation and building energy use. However, there is generally good coverage of the theoretical pathways in the literature.
- Studies of specific interventions within these pathways are more limited. While there are many intervention studies that focus on a particular outcome (such as climate or health benefits), it is less common to find studies where both GHG emissions and co-benefits have been measured. What we did find is heavily weighted towards certain pathways, such as transport or urban form (these tend to be pathways where it is comparatively easier to identify co-benefits).

- All of the intervention studies we looked at involved GHG emissions reduction, along with one or more co-benefit outcomes. The co-benefit outcomes can be generally grouped into one of four categories: health, liveability, air quality, and resource savings. The strength of findings varies across the interventions, with some co-benefits (such as those related to liveability) harder to quantify than those with more objective measures (such as resource savings).
- The practice review interviews highlighted the importance of factors such as combining an evidence base with local expert knowledge in order to deliver successful interventions.
- Intervening at neighbourhood, town, and city scales to reduce emissions cannot not be achieved by a single type of intervention. From the evidence, we identified three priority pathways that provide the opportunity for individuals, communities, and local and national agencies to act.

  1. Greening urban environments can be achieved through small-scale community-led interventions as well as broader-scale national and local authority initiatives.
  2. Changes to a low carbon design and operation of infrastructure networks can have far-reaching consequences for reducing embodies and operational emissions, and support wide-scale emission-reducing behaviour change.
  3. Increasing the compactness of urban form offers multiple avenues to reduce emissions through behaviour change, material use, and resource efficiency, and when done well, ultimately improve the quality and functioning of Aotearoa New Zealand's neighbourhoods, towns, and cities.

We have identified the following recommendations from our findings:

Regarding interventions to reduce emissions and support well-functioning neighbourhoods, towns, and cities:

- Provide decision-makers with the ability to understand, interrogate, and gather additional evidence so they can answer the question - 'how could it work here?'
- Match the type of intervention with who can successfully implement it. For example, individual people and sites can contribute significantly to low carbon urban form through greening of buildings and sites, but less so through changes to wastewater treatment infrastructure.
- Invest in a balanced portfolio of short-term, small-scale projects (such as greening of streets) with longer-term, complex programs (such as urban regeneration).
- Take a multi-scale approach to planning interventions so that changes at building, neighbourhood, network, and city scales can be enhanced by synergies between them. For example, optimising the extent and type of tree cover around buildings and along individual streets will be important for creating liveable and sustainable compact urban forms, and may be easier to achieve if planned for in advance.
- Consider how community values, needs, and knowledge, including Mātauranga Māori, can be reflected in emission reduction interventions, for example, the desire to support local food production and/or sharing knowledge.
- Consider how interventions can be staged to best achieve both emissions and community outcomes. For example, which communities will benefit the most from improvements to low carbon transport infrastructure?
- Take a long-term view so that interventions can be adapted as they evolve, and new opportunities can be seized as they arise.

Regarding the use of evidence to support decisions:

- Support a 'mosaic' approach to evidence that reflects the diversity of interventions, methods for evaluating and reporting, and information needs of information users. Develop ways of better combining and synthesising knowledge across evidence and intervention types to build a more wholistic view of interventions.

- Support the evaluation and reporting of interventions that reflect Te Ao Māori worldviews and incorporate Mātauranga Māori, including studies done by Māori with Kaupapa Māori research principles.
- Support the accumulation and sharing of knowledge with information users to better address uncertainties about what 'works', especially regarding novel and/or complex and wholistic interventions.
- Acknowledge that not all the knowledge required to inform decisions about emissions reduction through urban form can be sourced from formal, reported evidence.
- Develop ways to facilitate the integration of experience and expertise alongside formal evidence in ways that provide robustness and transparency.
- Support evaluation methods that enhance comparability across studies and evaluations, including geographical, environmental, economic, socio-cultural, and built environment features.
- Develop methods to aid the interpretation and translation by users of evidence to the Aotearoa New Zealand urban and cultural environment.

1 Introduction

Climate change is one of the most challenging issues we face today. The rapid industrialisation that occurred over the past few centuries led to widespread population growth, which has largely been accommodated by a vast expansion in the size and scale of urban areas. Although these processes did contribute to improvements in living standards, they are also responsible for significant environmental damage, as continuous growth has pushed against the ecological limits of our planet. Our unchecked use of fossil fuels has emitted huge quantities of greenhouse gases (GHG) into the atmosphere, resulting in climate change that now impacts our lives in a multitude of different ways (OECD & European Commission, 2020; The Intergovernmental Panel on Climate Change [IPCC], 2022).

A considerable share of GHG emissions can be attributed to urban areas. Results from NASA's Megacities Carbon Project highlight how urban areas, which account for just 2% of total land area, emit three-quarters of all fossil fuel carbon emissions globally (NASA, 2022). The way in which built environments are planned, designed, constructed, and used plays a major role in their impact on the environment (IPCC, 2022).

To reduce this impact, the recent Intergovernmental Panel on Climate Change (IPCC) report recommends that governments develop climate budgets, climate emergency funds, and carbon reduction plans to support a low carbon future. According to the IPCC's report (2022), 30% of GHG emissions come from transport, commercial, and residential energy use globally. One of the main ways cities can cut GHG emissions is through repurposing and retrofitting buildings — choosing low carbon materials and low emission technologies in building construction. Another way is to create human-centred urban areas with a focus on compact design, co-location of jobs and housing, and increased use of active and public transport (IPCC, 2022).

Reducing GHG emissions in urban areas will come at a significant cost, but it also presents a unique opportunity to do things differently. Besides climate change, the built environment influences a range of other outcomes, e.g., health and wellbeing. By incorporating co-benefits into strategies for mitigation and adaptation this can also support the development of well-functioning urban communities. We also need to consider cities across a range of different spatial scales, from individual buildings and structures to the whole city. There is a growing interest in exploring how cities function at the neighbourhood scale, due to the need to address the contributing factors underlying urban outcomes. Evidence of this can be seen in the increasing number of studies which apply a Life Cycle Assessment (LCA) to neighbourhoods (Lotteau et al., 2015).

In Aotearoa New Zealand, the recently released emissions reduction plan established the direction for climate action over the next 15 years. Published by the Manatū Mō Te Taiao Ministry for the Environment, the discussion document '*Te hau mārohi ki anamata:* Transitioning to a low-emissions and climate-resilient future' established the opportunity for change through urban form (Ministry for the Environment, 2021).

> *"… the scale of the change is an opportunity to address other long-standing challenges in Aotearoa. We must integrate the reduction measures with strategies for industry, infrastructure, housing, and urban development; fiscal management; and plans for building resilience to the physical effects of climate change." (p. 22)*

> *"Understanding the emissions impact could inform strategic, spatial, and local planning and investment decisions, and drive emissions reductions going forward. There are major opportunities in planning and investing for a more compact mixed-use urban form, oriented around public and active transport." (p. 42)"*

The work that needs to be undertaken to transform these sectors to align with GHG emissions reduction goals is substantial and will require the allocation of significant resource (Ministry for the Environment, 2022). It therefore makes sense to coordinate climate action to deliver co-benefits where possible.

The development of an evidence base is one way to support urban practitioners to make informed decisions about changes to neighbourhoods and cities. The Te Tūāpapa Kura Kāinga Ministry of Housing and Urban Development originally identified the need for evidence to support decision-making, which was then included in the BRANZ Prospectus as a knowledge gap. Evidence will assist local authorities to consider a wider range of interventions that they may have been able to access, along with information on how suitable an intervention may be for their situation. Useable evidence can help councils make, and fund, decisions aligned with reducing GHG emissions and adapting to climate change.

This project started with the question:

> What evidence exists internationally on the potential benefits of neighbourhood to city-scale planning to reduce greenhouse gas emissions?

Methodology

The aim of this project was to form an evidence base of interventions addressing three aspects: the reduction of GHG emissions (domain 1) through the urban form neighbourhoods, towns, and cities (domain 2); while also delivering co-benefits related to well-functioning urban communities (domain 3). The key relationships between the three aspects are summarised in Figure 1 below.

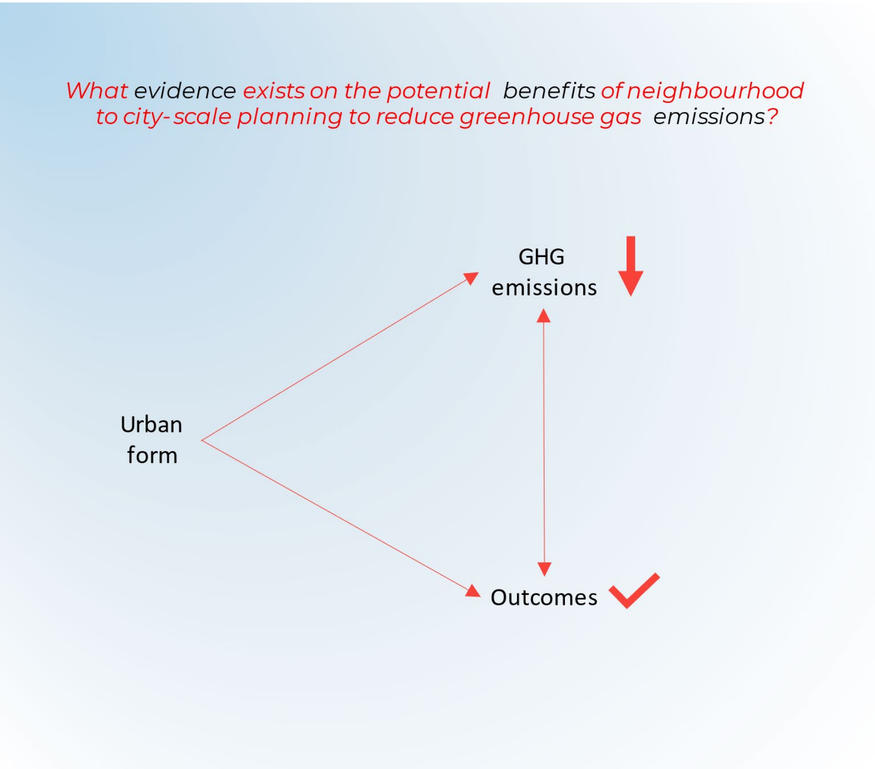

Figure 1: The relationships of interest between GHG emissions, urban form, and community outcomes

The evidence base was formed in six steps:

1 Scoping workshop and interviews with research partners to understand

   (a) their experience of how urban form was related to co-benefits of emission reduction, and
   (b) their views on what counts as useful evidence.

2 Literature review of evidence of interventions and changes to urban form.
3 Practice review of real-world cases and lessons learnt.
4 A scan of current evidence base platforms and their pros and cons.
5 Sense-making workshop with research partners to determine key features of the evidence base format.
6 Designing a useable intervention evidence base prototype.

We worked with potential users of an evidence base so that the output would meet the needs of decision-makers and be useable and accessible. The evidence users engaged with as research partners over the course of the project were all invested in reducing emissions and responsible in some way for urban form. They included local authorities – Christchurch City Council, Te Kaunihera o Te Tairāwhiti Gisborne District Council, and Rau Tipu Rau Ora (RTRO) Tuara, as well as central government agencies – Kāinga Ora – Homes and Communities and Waka Kotahi (NZ Transport Agency) and Local Government New Zealand.

Guidance was provided by research partners through two interactive workshops and follow-up interviews on what evidence we should be seeking and the form of the evidence base outputs.

The scoping workshop provided the parameters for the evidence base and therefore the scope of the literature review. The literature review step sought to identify if evidence exists of the pathways between urban form, GHG emissions, and wider benefits, describe the nature of relationships (including the direction and magnitude of associations), and any key contextual factors that might affect how generalisable the findings are. A secondary purpose was to identify critical gaps in the published evidence base — i.e., what do we not know?

The literature review undertaken for this project has run in parallel with one commissioned by Waka Kotahi on interventions to reduce light vehicle travel[1] which, given the significance of transport to GHG emissions, had a useful crossover in the literature covered. Relevant material has therefore been included in both reports. Both projects found relatively few studies and limited information to make effectiveness and transferability comparisons. This report also includes commentary on the 'evidence conundrum' applicable to both reviews.

We included a specific focus on Mātauranga Māori, recognising that Mātauranga Māori and indigenous knowledge would be an important addition to an evidence base for New Zealand practitioners. To support this focus, a Māori researcher on the research team was charged with specifically searching and reviewing Māori and indigenous evidence. Despite this targeted searching, we were unable to find evidence with a Mātauranga Māori focus that met the research criteria.

To complement the literature review, practice reviews of four real-world cases were done using in-depth interviews, including one that incorporated Mātauranga Māori.

The final steps of the project brought the knowledge and insights gained to a second sense-making workshop with our research partners where the design parameters for the evidence base itself were agreed. The digital evidence base was then developed, populated with the outputs of the literature review.

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[1] Research Report 707 A narrative literature review of the effectiveness of interventions to reduce light vehicle travel. https://nzta.govt.nz/resources/research/reports/707/

2 Scoping workshop

The scope of the research was broadly determined by the topic (i.e., evidence for relationships between urban form, emissions, and co-benefits). It was further refined in consultation with the research partners through exploration of their understanding of a) the key pathways between the three elements and b) the nature of evidence.

In February 2022, an interactive workshop was held online using Teams and a Miro whiteboard. Two small-group exercises were run using the design sprint prompts shown in Figure 2:

Figure 2: Design sprint prompts

The key conclusions from the workshop were:

The conceptual pathways between urban form, wellbeing, and emissions reduction

- *We determined that a well-functioning neighbourhood, town, or city is one where multiple facets demonstrate positive and equitable economic, health and wellbeing, cultural, social, and environmental outcomes over many generations. These are achieved through diverse, inclusive, mixed-use, and vibrant communities that reconnect with nature and create a sense of place. These neighbourhoods provide viable, timely transport options for connecting with places and services that support wellbeing, are responsive to climate change both through a reduction in carbon* *emissions and adaptation to future climates and environments, incorporate and support the transition to a circular economy and leave behind a positive legacy for future generations.*

The nature of useful evidence

- *We determined that the [useful] evidence is impartial, trusted information that can stand up to challenge and scrutiny. Users of evidence must understand and respect the relationships between knowledge holders, those desiring knowledge, and those generating evidence. The evidence required to support our development towards these communities must come from a diverse range of sources and contexts to be able to reflect and encourage the aspirations of diverse stakeholders on this journey. There is a hierarchy of 'evidence' that reflects the scale, timeliness, and quality of data available: its use should be determined with care.*

The principles and values around knowledge

- *Evidence needs to include local Māori knowledge (customs, traditions, values), and be able to connect with 'on-the ground' experiences. We agreed that looking to other cultures should go beyond the developed/Euro centric world to consider positive outcomes in other jurisdictions as well as consider both academic evidence and lived experience as valid forms of evidence to influence the various stakeholders: including political groups, policy makers, governments, business leaders, and tangata whenua.*

Based on workshop outputs, a comprehensive set of search terms for urban form and community benefits were generated to be applied in the literature review of evidence (Table 1).

Table 1: General search topics for the literature review identified in the workshop

Category	General search topics
Urban form	• Accessible: o To key destinations o To viable transport modes (including public transport) o By everyone, and by all communities • Walkable • Cyclable • Nature (green and blue spaces/infrastructure, ecological corridors, networks) • Biophilia • Salutogenic design (health-promoting) • Therapeutic environments • Affordable housing (including the cost of accessing key destinations) • Public transport • Sustainable materials and construction practices • 10-, 20-, & 30-minute neighbourhoods
Benefits/outcomes	• Connectedness and belonging: o To people o To whenua/place o To pride and satisfaction • Sense of community: o Trust o Social cohesion • Healing • Health domains: o Mental health o Cultural health o Social health

	• Health behaviours:
	  o Physical activity
	  o Social activity
	  o Harmful health behaviours
	• Consumption/consumerism
	• Safety:
	  o From traffic
	  o Personal safety (e.g., at night)
	  o For vulnerable users (e.g., children)

Emissions	• Circular economy • Energy resilience
Principles and concepts	• Inequality • Intergenerational inequality • Lifestyle • Legacy • Accommodating diversity of values and needs (e.g., the 8–80 years concept) • Urgency • Addressing injustices

3 Literature review of evidence

The overall aim of the review was to identify and describe the evidence for making changes to urban form in ways that can lead to GHG emissions reduction and provide co-benefits for communities. The review process was guided by the outputs from the scoping workshop.

Methodology

The literature review was carried out in two stages. The first identified the relationships explored in the literature between urban form, GHG emissions, and community outcomes (co-benefits). The aim of this stage was to establish an understanding of the pathways connecting these three factors to develop a framework of the interactions between them. Using search terms from Table 1, a total number of 733 articles were found, and screened using their titles and availability. Of the 733 initial articles, 174 articles went to the second screening of the abstract and content. Articles that did not include content on all three aspects (urban form, GHG emissions, and co-benefits) were excluded. In the end, 58 articles were reviewed to extract their themes and ideas. These articles included both observational studies and reviews.

The second stage developed the evidence base with reports of interventions and changes in urban form with associated emissions reduction and co-benefits in each domain. To make the most of available knowledge, papers that modelled changes were also included. The 'modelling of change' approach takes a specific change and models what could happen if it were applied elsewhere. The approach requires a theory of how the change causes the effect and builds in assumptions and relevant parameters about the conditions surrounding the change that would be required to achieve the same outcome. The value of modelled change reports is therefore dependent on sufficient information being available to operationalise the theory without undue bias. A total of 20 papers were included in the final evidence base and are summarised in an interactive evidence base dashboard.

While comparative observational studies were of interest, this review of evidence focused on what has been done to urban form that can also deliver emissions reduction and community benefits. Cross-sectional comparisons and descriptive observations are useful to inform underlying mechanisms, but do not necessarily pinpoint what changes are needed and how to make them. Where helpful, the mechanisms they illuminate are discussed but are not included in the final evidence base.

The two-stage review process allowed critical gaps to be identified — that is, pathways reported and discussed in the literature, but which are not well supported by evidence from interventions and modelling of change.

Findings

The first stage of the review identified six GHG reduction domains: greening (including nature and urban agriculture), urban form, mobility and transportation, energy, water, construction, and smart technology. Overall, the review of the literature shows that two domains, namely transport and energy use of buildings, were more frequently studied.

Figure 3 summarises the relationships found in the literature between GHG, urban form, and community co-benefits found in stage 1. In this figure, factors have been connected directly to CO_2 or through a midway element to explain the connection to CO_2. This figure summarises the connections between the intervention domains and carbon emissions or the co-benefits of creating a well-functioning neighbourhood. Figure 3 also shows some of the design intervention factors had a direct relationship with the urban form. The connecting lines indicate where the literature supports a relationship or pathway between, for example, water and co-benefits.

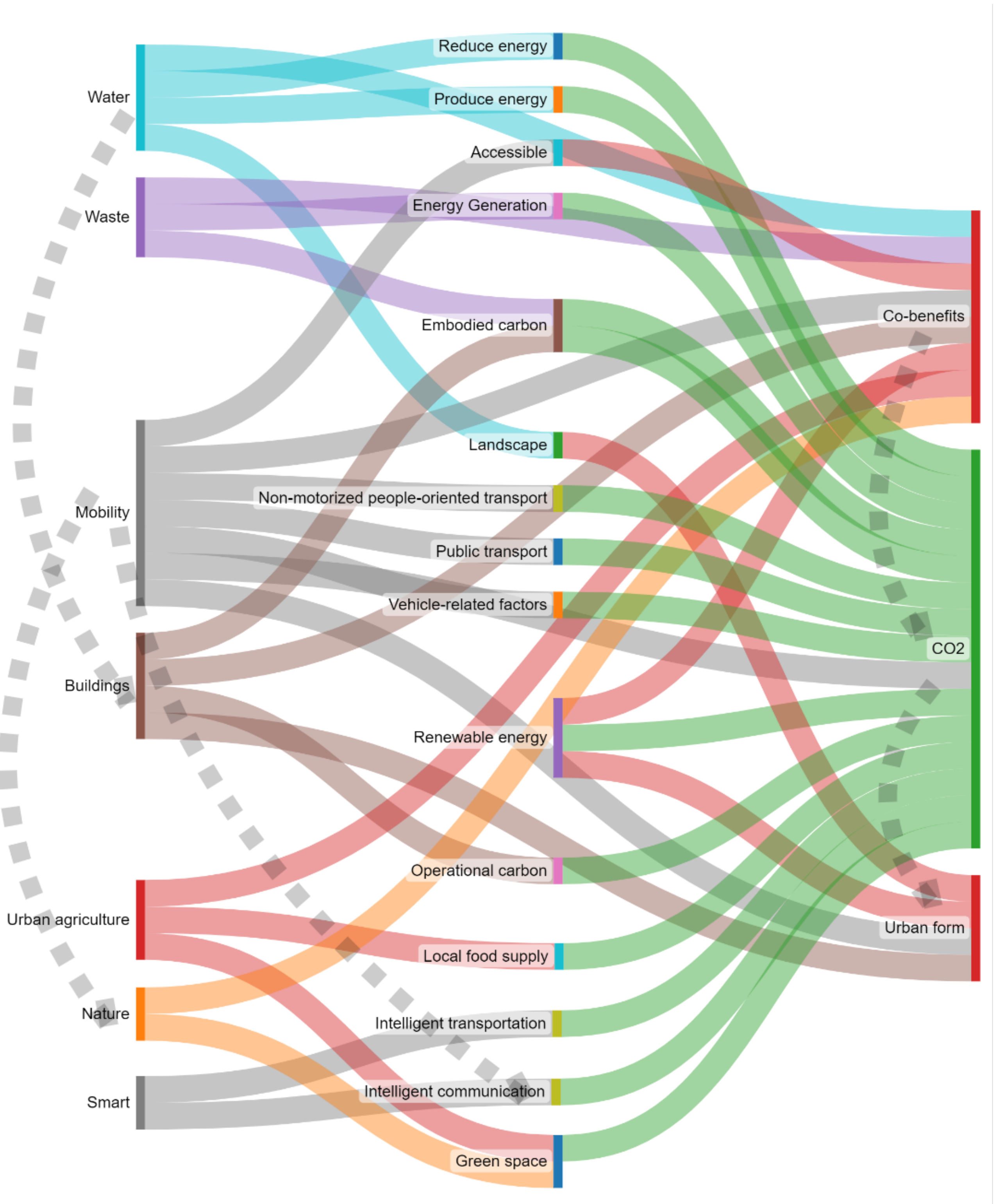

Figure 3: Influential factors on GHG reduction in urban form

Figure 4 further breaks down the domains into specific topics identified in the first stage of the literature review. 'Urban agriculture' and 'Nature' have been combined into 'Urban greening' and 'Smart' and 'Building' have been combined into 'Construction and 'smart' technology'. These were used to further refine search terms for stage 2 of the literature review.

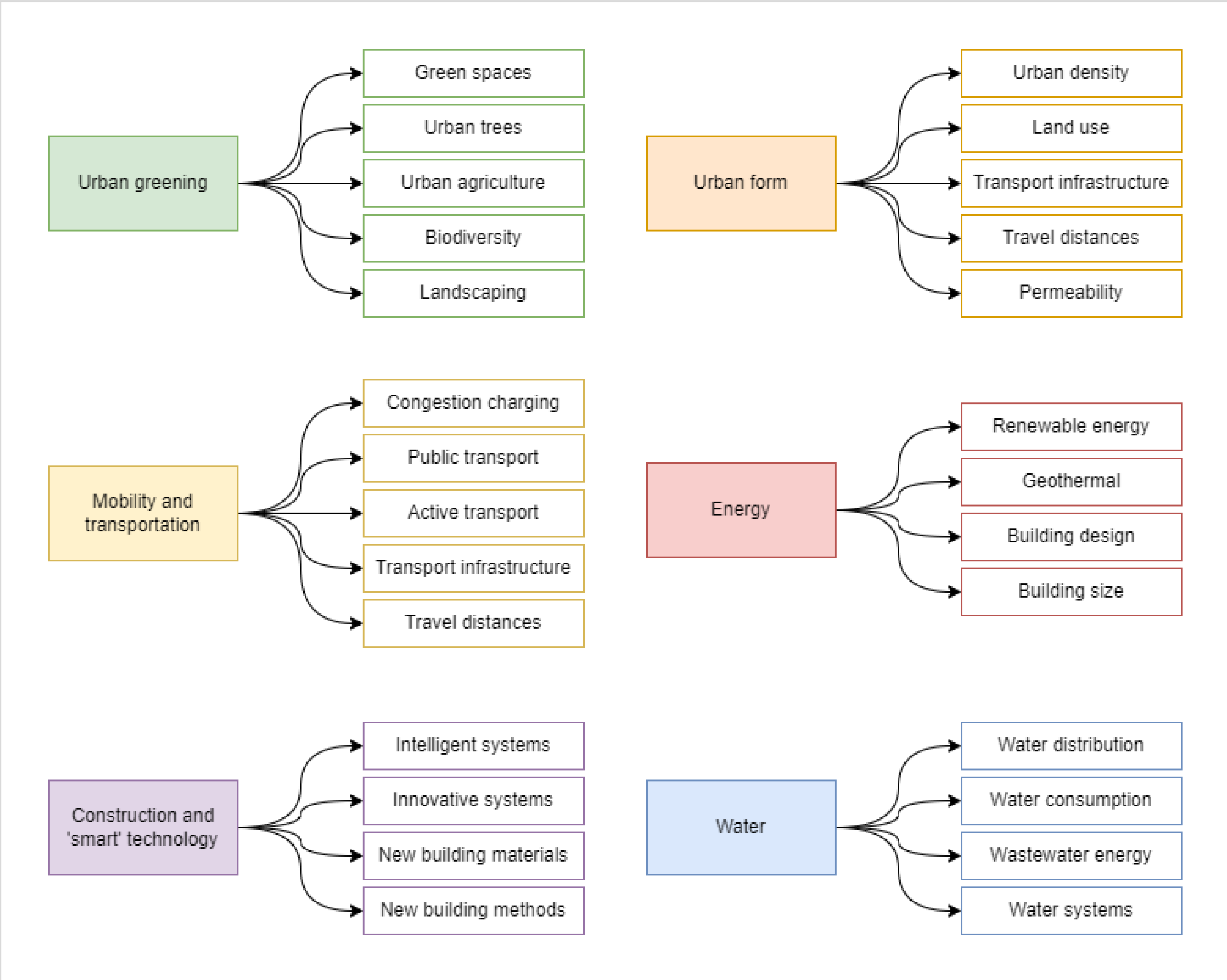

Figure 4: Topics within each category of the literature review

The following subsections further develop each of the six GHG reduction domains. Within each of the domains, the pathways for reducing GHG and community benefits are discussed along with intervention-based evidence for those pathways. Interventions are starred in the text and summarised at the end of each section. Some interventions were relevant to multiple domains and are discussed accordingly in each section. A total of 20 studies were included in the intervention evidence base. Details of each study have been summarised in the evidence base dashboard.

Greening: nature and urban agriculture

Many studies have investigated the role of urban trees and green areas as a means of carbon sequestration and their relationship with active transport and liveability. House-Peters & Chang (2011) investigated the intertwined relationship between urban land cover and external water consumption as a result of climate change, and concluded that increasing the fraction of trees would improve urban cooling and reduce external water consumption.

Kiel (2017) studied the harmony between greenways and public transportation and found that greenways can provide community benefits — e.g., social cohesion, promoting physical activities, natural beauty, economic development, and ecological restoration — as well as encouraging emission-free transportation and the sequestering of carbon. Cox et al (2017) demonstrated in their research that nearby natural areas could have a strong relationship with creating ecological place meaning and environmental awareness, especially for children.

Findings from a descriptive case study by Tuğluer et al. (2017)* showed that tree inventory data, including species, leaf surface area, age, and height may increase the carbon sequestration and decrease the amount of CO_2 emitted. They also found numerous co-benefits associated with urban trees, e.g., improved air quality, reduced noise pollution, and enhanced liveability.

Several papers also discussed the equity implications of neighbourhood greening. In some cities, the local government requires property owners to take care of their adjacent public trees. Alves Carvalho Nascimento and Shandes (2021) identified this requirement as a barrier to maintaining trees, particularly in lower-income areas. As a result, tree canopy extent is diminishing in some locations. Issues of equity were also highlighted in a study by Greene et al. (2021) which determined that urban ecosystem services distribution is positively correlated with residents' ownership and negatively impacted by socioeconomic status. Cooper et al. (2021) demonstrated that large cities score lower in terms of distributing native biodiversity compared to smaller cities when looking at the neighbourhood scale, which is dependent on the management system in place. They further proposed that a robust policy can better preserve biodiversity and overcome the size and population, which can have a role in carbon sequestration (2021).

Bochner et al. (2018) found that a community garden was a means for a neighbourhood to reduce carbon emissions by sequestering carbon and reducing transportation emissions, while also increasing social cohesion and population health. Food growing urban gardens or green surfaces in buildings can also take advantage of rainwater collection and support the local food supply while helping mitigate urban heat (González et al., 2022). Some benefits of urban agriculture include economic benefits, the creation of jobs, the efficient use of public spaces, increasing resiliency, decreasing depression, improving public health, better management of energy, waste, and water, and softening the heat island effect (Kusumanagari & Ellisa, 2021; Mohammadi & Ebrahimi Nia, 2019).

While not done in an urban context, a nevertheless helpful study by Sha & Li (2020) showed that grazing intensity in rural neighbourhoods could be an important measure when it comes to carbon sequestration — since grassland improvement is a human-related factor, it can be appropriately managed. For example, light to medium grazing was beneficial because it improved the topsoil, affecting vegetation growth (Sha & Li, 2020).

Greenery can also be included as part of the design of buildings. The descriptive case study reported by Peñalvo-López et al. (2020)* looked at the impact of installing a green roof on a building's carbon impact and energy use. They found that a green roof can contribute to the abatement of CO_2 emissions while also reducing the energy required for heating and cooling.

Table 2 outlines the intervention studies included in the greening domain.

Table 2: Greening intervention studies

Title	Author, date, & location	Intervention /	Co-benefits
Study of the Improvement on Energy Efficiency for a Building in the Mediterranean Area by the Installation of a Green Roof System	Peñalvo-López et al. (2020), Spain	The installation of a green roof on a public building (in the form of a rooftop garden).	Resource savings: Green roofs reduce the building's energy demand for heating and cooling.
Ecological importance and role in carbon sequestration of urban trees (in case of Isparta Anadolu neighbourhood)	Tuğluer et al. (2017), Isparta, Turkey	The use of urban trees to sequester carbon.	Liveability: Urban trees reduce noise pollution, enhance people's wellbeing, and increase recreational opportunities.

			Air quality: Urban trees were found to increase the air quality by filtering pollutants.

Urban form

There is extensive literature examining the relationship between urban form and wellbeing that is relevant to reducing emissions, including work undertaken in Aotearoa New Zealand. Much of the work is focused on the relationship between urban form and mobility behaviours, notably physical activity-related walking and cycling. Overall, numerous studies have found that living in urban form characterised as more walkable is associated with higher levels of transport-related physical activity (Smith et al., 2017).

For example, the observational International Physical Activity and the Environment Network (IPEN) study examined the relationships between urban characteristics and physical activity in 14 cities across 10 countries (Cerin et al., 2014). The Aotearoa New Zealand cities included Ōtautahi Christchurch, Te Whanganui-a-Tara Wellington, and Tāmaki Makaurau Auckland (at the time, Waitakere and North Shore cities). The Aotearoa New Zealand arm of IPEN compared levels of physical activity — reported and observed using accelerometers — amongst residents living in areas characterised as more or less walkable (Witten et al., 2012). While the study was cross-sectional, it was able to shed light on causal mechanisms by controlling for potentially confounding individual, household, and neighbourhood factors, including self-selection factors. The study found that residents living in more walkable, more aesthetically pleasing streetscapes, with a greater density of local destinations, tended to have higher levels of physical activity — much of which was transport-related walking. The difference in physical activity levels between the most and least walkable neighbourhoods was approximately 30% (Witten et al., 2012), after accounting for confounding factors.

Research into the relationship between neighbourhood characteristics, mobility, and wellbeing has shed light on the importance of accessibility to wellbeing resources. Urban form models e.g., 20-minute cities (Webb-Liddall, 2021) demonstrate the potential of urban planning and design to reduce the dependence on private vehicle use and ownership, by reducing the distance and time taken to get to everyday destinations. The 20-minute city approach (or 15 or 30 minutes, depending on the context) encourages us to re-think the spatial-temporal provision to communities of the opportunities to participate locally in the workplace, education, play, access to healthy foods, goods, and services, as well as participating socially and culturally, without needing to drive or travel long distances. It emphasises the importance of considering how things work together, rather than thinking of individual buildings, modes, or activities, so that it creates the 'opportunity structures' for wellbeing (Baum & Palmer, 2002). Because of the necessary interaction between what is built and how people engage with structures and each other, the changes needed to retro-fit places such as Kirikiriroa Hamilton into a 20-minute city will be comprehensive and complex.

A range of studies have looked at various interventions relating to urban form, carbon emissions, and co-benefits. Two studies in China (Guan et al. (2019)* and Liu et al. (2017)*) modelled the relationship between urban form and transport emissions, finding that the use of low-carbon transport modes was associated with urban form characteristics e.g., higher population densities, better access to services and amenities, and pedestrian-friendly streets. Senbel et al. (2014)* compared case studies of different types of urban form in Vancouver, Canada, finding that the developments associated with the lowest GHG emissions were medium to high density and close to urban centres. Howden-Chapman et al.'s (2020)* case studies re-evaluated several previous natural experiments, one of which was the use of 'special housing areas' to support housing development. They found that low-density development was not associated with carbon savings, instead, this could be achieved through higher density development. This finding is supported by Hachem (2016)* and Salter et al. (2020)*, with both modelling studies reporting carbon savings associated with more compact development. Hachem (2016)* also found that streets designed for alternative transport modes and shorter distances to business centres played a role in carbon reductions. All intervention studies noted a range of co-benefits alongside emissions reduction which are outlined in Table 3.

Table 3: Urban form intervention studies

Title	Author, date, & location	Intervention	Co-benefits
Does neighbourhood form influence low-carbon transportation in China?	Guan et al. (2019), Chengdu, China	Neighbourhood form of varying densities and characteristics.	Liveability: Compact urban forms were associated with more liveable urban environments (better spatial connectivity).
Impact of neighbourhood design on energy performance and GHG emissions	Hachem (2016), Calgary, Canada	Neighbourhood form of varying densities and characteristics.	Liveability: Compact urban forms were associated with more liveable urban environments (better spatial connectivity). Resource savings: Higher density development was found to use less energy.
Evaluating natural experiments to measure the co-benefits of urban policy interventions to reduce carbon emissions in Aotearoa	Howden-Chapman (2019), Aotearoa	Policies related to active travel infrastructure and housing development.	Liveability: Higher density development was associated with better stormwater retention.
Neighbourhood-scale urban form, travel behaviour, and CO2 emissions in Beijing: implications for low-carbon urban planning China?	Liu et al. (2017), Beijing, China	Neighbourhood form of varying densities and characteristics.	Liveability: Compact urban forms were associated with more liveable urban environments (better spatial connectivity).
Iterative 'what-if' neighbourhood simulation: energy and emissions impacts	Salter et al. (2020), British Columbia, Canada	Neighbourhood form of varying densities and characteristics.	Resource savings: Infill development (compact houses) were found to use less energy than average-sized houses.
Compact development without transit: Lifecycle GHG emissions from four variations of residential density in Vancouver	Senbel et al. (2014), Vancouver, Canada	Neighbourhood form of varying densities and characteristics.	Liveability: Compact urban forms were associated with more liveable urban environments (better spatial connectivity). Resource savings: Higher density development was found to use less energy for heating and cooling.

Mobility and transportation

Mobility and transportation have been one of the main topics that has been studied in terms of its relationship to the amount of carbon emissions in urban areas. Active transport, mode choice, public transport, walkability, cyclability, the use of fuel-efficient or electric vehicles, are among the factors studied in this area. However, transportation has always been interrelated to other aspects as varied as land use, health outcomes, and income levels (Singer, 2021; Steinmetz-Wood & Kestens, 2015; Yoon et al., 2017). For example, Bochner et al. (2018) and Bonaccorsi et al. (2020) reviewed a variety of factors which not only have an influence on low carbon transportation but can contribute to other aspects of a well-functioning neighbourhood. They included residential density, land-use mix, pedestrian-friendly infrastructure, street connectivity, intersection hazards, traffic signs, bike lane amenities, aesthetics of the streetscape, community engagement, pollution, and lighting.

Xia et al. (2015)* did a Health Impact Assessment (HIA) of transport scenarios on health and GHG emissions. They modelled scenarios comparing business-as-usual to alternative transport settings, investigating the impact on emissions and health in the proportion of trips by active and public transport in Adelaide, Australia. They found that even a modest shift towards these modes would have significant impacts on both emissions and health outcomes (due to increases in physical activity and decreases in exposure to air pollutants). Similarly, Rodrigues et al.'s (2020)* HIA (Health Impact Assessment) in Porto, Portugal and Perez et al.'s (2015)* modelling in Basel, Switzerland found that increases in the use of alternative modes would result in fewer GHG emissions and fewer disability-adjusted life years (DALYs) due to significant reductions in cardiovascular diseases in particular.

Ways to encourage people to use low carbon transport forms (e.g., active transport modes) have been widely studied, including some intervention studies. Guan et al. (2019)* showed through modelling potential changes to urban form that people would be more likely to use low carbon transportation when there is enough access to public transport, high land-use diversity, and spatial connectivity within neighbourhoods. In Aotearoa New Zealand, a quasi-experimental study by Chapman et al. (2018)* looked at the Aotearoa Model Communities Programme, which funded investment in active travel, including walking and cycling infrastructure, media campaigns and events, and cycle skills training. They valued both the reduction in CO_2 emissions as well as the health benefits from the savings in DALYs, with the overall cost/benefit ratio of the interventions estimated to be 11 to 1. Mehaffy's study (2018) outlined some other strategies, including making more attractive and accessible transit stops, walking and biking paths, increasing street permeability, and the use of pricing and economic rewards. Sunarti et al. (2018) also found that pavement quality, trees, seating features, and pedestrian crossings are among the physical improvements that encourage people to walk. Land-use mix or adding a variety of commerce and community gathering places close to walking paths can strengthen a neighbourhood's walkability in reducing carbon emissions. Liu et al. (2017)* modelled urban form and infrastructure changes that could reduce travel-related CO_2 emissions, with contrasting results. Results showed that although land-use mix, availability of public transport facilities, and low-speed streets might increase the amount of short-distance trips taken, they reduce CO_2 emissions by lowering long-distance trips and by encouraging people to low-carbon transportation options. This is supported by Yang & Cao (2018), who studied the effects of the neighbourhood built environment on CO_2 emissions from transport. While almost all the built environment elements had an impact, the more indirect effects (e.g., the distance to destinations) made a larger difference.

Metz (2018) compared the effects of congestion charging in London, Stockholm, and Singapore finding that, to different extents, it reduced the number of vehicles on the road and therefore emissions. For example, in Central London where a congestion charge scheme was introduced, the initial impact of the scheme was a 33% reduction in car traffic entering and leaving the charged zone. In Singapore, the Electronic Road Pricing (ERP) system included a central restricted zone (setting speed limits in urban roads and expressways) and relatively low charges on four additional zones with charges varying depending on vehicle class, time of day, and location. As a result, a reduction of approximately 10–15% in traffic volume was reported in the central business district. In Stockholm, congestion was quantified based on floating car measurements or from traffic cameras. The study estimated a 15% reduction in total road use within the charged cordon while the reduction in the total number of vehicle passages over 24 hours was 22%. In terms of the impact on air quality and health, the total traffic-related emissions in the cordon area of NOx and PM10 fell by 8.5% and 13%, respectively.

Addressing the needs of people through urban form has been reviewed in many papers. Age-friendly accessibility needs (Eom, 2015), traffic safety, aesthetics, sidewalk quality, physical barriers (Chiang et al., 2017), and satisfying the shade needs of pedestrians (Villarino, 2021) have also been explored. Dash (2020) focused on ageing population walkability and suggested reducing travel-related carbon by adding seating locations, conversational seating in walkways, loop walking, visibility for security and safety, better traffic safety, and restricted vehicular access as some features to be included in the neighbourhood design.

The importance of socioeconomic factors for understanding the transport-urban form relationship has been widely explored, but the results have not been consistent since there are either many other factors involved, or they are context-specific. Many studies support the idea that active transport is linked with socioeconomic status and social environments which can act as barriers to the effectiveness of urban design interventions. For example, Steinmetz-Wood and Kestens (2015) found that the relationship between urban density and active transport was weaker for trips originating from neighbourhoods with lower socioeconomic status. One reason socioeconomic factors might modify the relationship between urban form and travel behaviours is the degree of exposure to residential environments. Ivory et al. (2015) hypothesised that individual-level factors (e.g., gender, working status, car access, and income) could act as proxies for how much time people spent in their residential environments. Analysis showed stronger associations between urban form and walking for women, restricted car access, not working full time, and lower income levels. Singer (2021) showed that transit-rich urban forms can be more affordable for low income households because they reduce the cost of transport.

A prototyping study on factors to reduce GHG emissions identified neighbourhood design (including density, land use, and building performance) and distance to business centres as the two most influential factors (Hachem, 2016). Other researchers also emphasised the importance of urban form density through its role in encouraging walkability and the added value of supporting businesses. However, they found a diminishing point, and high densities may not be as effective as medium-density neighbourhoods. The combination of walkability, cycling, and public transport is also a key factor. They concluded therefore that walkable, bikeable paths and public transportation work better together in medium density areas and support businesses better (Lewis & Adhikari, 2017; Marti, 2018; Marti et al., 2017). Meanwhile Senbel et al. (2014)* compared cases of compact development with low-density development, finding that even when good public transport access was not available, compact development was associated with fewer embodied and operational emissions, while also encouraging more active travel.

Table 4 outlines the intervention studies relating to mobility and transportation.

Table 4: Mobility and transportation intervention studies

Title	Author, date, & location	Intervention	Co-benefits
A cost benefit analysis of an active travel intervention with health and carbon emission reduction benefits	Chapman et al. (2018), Ngāmotu New Plymouth and Heretaunga Hastings, Aotearoa	Investment in cycling facilities including bike paths and bike parking, as well as cycle training.	Health: An increase in active travel was associated with fewer instances of cardiac diseases, diabetes, cancer, and respiratory disease; and disability-adjusted life years. Liveability: The various cycling infrastructure initiatives helped make cyclists feel safer.
Neighbourhood-scale urban form, travel behaviour, and CO2 emissions in Beijing:	Liu et al. (2017), Beijing, China	Neighbourhood form of varying densities and characteristics.	Liveability: Compact urban forms were associated with more liveable urban

implications for low-carbon urban planning China?			environments (better spatial connectivity).
Transport-related measures to mitigate climate change in Basel, Switzerland: A health-effectiveness comparison study	Perez et al. (2015), Basel, Switzerland	Transport policies that support active travel modes.	Health: A reduction in travel by private vehicles and an increase in travel by active modes was found to prevent premature deaths due to less exposure to air pollution. Air quality: A decrease in travel by private vehicle was found to reduce the total amount of particulate matter emitted.
Health economic assessment of a shift to active transport	Rodrigues et al. (2020), Porto, Portugal	Transport policies that support active travel modes.	Health: An increase in active travel was found to reduce the mortality risk for a range of diseases (cancers, diabetes, heart disease, and cerebrovascular disease) as well as reduce traffic injury risk. Air quality: A decrease in travel by private vehicle was found to reduce the total amount of particulate matter emitted.
Compact development without transit: Lifecycle GHG emissions from four variations of residential density in Vancouver	Senbel et al. (2014), Vancouver, Canada	Neighbourhood form of varying densities and characteristics.	Liveability: Compact urban forms were associated with more liveable urban environments (better spatial connectivity). Resource savings: Higher density development was found to use less energy for heating and cooling.
Traffic-related air pollution and health co-benefits of alternative transport in Adelaide, South Australia	Xia et al. (2015), Adelaide, Australia	Transport policies that support active travel modes.	Health: Increases in the use of active and public transport were associated with fewer deaths and disability-adjusted life years. Air quality: A decrease in travel by private vehicle was found to reduce the total amount of particulate matter emitted.

Energy

Another influential domain that has been relatively studied widely is the energy performance and embodied carbon of buildings which are responsible for a great share of carbon emissions. While the primary focus of many studies is on individual buildings, some have located buildings within their wider urban form, for example, going outside the building boundaries to consider effects on nearby pedestrians.

Studies on neighbourhoods' emissions in terms of the proportions of offices, single-detached houses, apartments, retail shops, and townhouses do not have consistent results. Singh & Hachem-Vermette (2019) showed that by increasing the neighbourhood proportion of offices, single-detached houses, and townhouses, emissions of waste-to-energy plants would decrease. By contrast, emissions will increase with the rise of retail and apartment buildings in a neighbourhood (Singh & Hachem-Vermette, 2019). Another study by Gonzalez (2022) on waste-to-energy transformation indicated that neighbourhoods would gain environmental and economic benefits, and apart from reducing household demands, there would be many benefits and reduced emissions from preventing the waste from going to landfills and instead managing it locally.

Balaban & de Oliveria (2017)* comparative case studies and MacNaughton et al. (2018)* modelling studied the effects of sustainable/green buildings in several countries, including the United States, Germany, and Japan. They found that green-certified buildings saved energy costs and had substantially reduced GHG emissions compared with buildings that are not green-certified. In addition, these buildings were also associated with co-benefits e.g., better indoor air quality and less heat emissions, and better conditions for pedestrians. Building renovations can also make a difference to reducing emissions, as they can reduce the energy required to heat and cool the building (Ferreira et al., 2017)*.

Lausslet et al. (2021)* modelled changes to zero carbon neighbourhoods in Norway. They examined the climate change mitigation potential of different scenarios of material efficiency strategies and found that a sufficient floor area per inhabitant, low carbon intensity materials, reusing materials, and good maintenance were some of the most efficient strategies. To have a greater impact, they proposed that strategies should target the near future since the current construction peak, future uncertainties, and technological improvements in low carbon materials all lead to requiring current urgent action. Singer (2021) also stated that providing affordable housing, i.e., smaller houses without parking, creates affordable units and reduces the energy use of units by reducing the floor area.

Embodied and operational carbon is indirectly affected by the waste generation in a neighbourhood and the recycling behaviour of its residents. Crociata et al. (2016) investigated the social forces to encourage recycling behaviour and showed that it could be a contagious behaviour among communities. Many researches have investigated ways to increase people's recycling behaviour, and found viable suggestions (Roy et al., 2019). Pei (2019) showed that community attachment could positively impact recycling. Some further successful strategies to reduce the operational and embodied carbon of buildings in a neighbourhood are discussed by Bochner et al. (2018), including funding weatherisation for ageing housing, timely inspection and maintenance of rental housing, demolishing unfit properties, and helping seniors with repair and maintenance of their houses.

Energy communities[2] can contribute to a low carbon neighbourhood's energy system using small-scale batteries and photovoltaic systems. However, there are some conditions for them to be effective. Apart from the operational efficiency in the energy community, they should have high local consumption, less need for the grid connection capacity, and high local renewable generation (Zwickl-Bernhard & Auer, 2021a)*. Another study by these authors indicated that local geothermal sources could be used for heating and cooling services and be a feasible option for an energy community (Zwickl-Bernhard & Auer, 2021b). There needs to be enough evidence of the technical aspects and costs of creating a self-sufficient neighbourhood with renewable energies (Grosspietsch et al., 2018), but all these investigations have been done in specific locations, and more studies are needed to generalise the results.

[2] Energy communities are "citizen-driven energy actions that contribute to the clean energy transition, advancing energy efficiency within local communities" (https://energy.ec.europa.eu/topics/markets-and-consumers/energy-communities_en).

The energy efficiency of buildings has also been shown to be improved with green roofs. Peñalvo-López et al.'s (2020)* descriptive case study looked at the impact of a newly installed rooftop garden on a building in Spain on the use of heating and cooling systems, and found substantial benefits. On a normal summer day, the green roof reduced the building's energy demand for cooling by 30%, and in the winter, energy for heating was reduced by about 15%. This suggests that while green roofs can be beneficial in different seasons, they are particularly useful in warmer conditions.

Energy can also be saved through effective management of urban water. Sokolow et al. (2016)***** did an HIA on various water conservation strategies in Southern California, finding that expanding the use of recycled water resulted in energy savings.

A "rebound effect" is one of the concepts to consider when there are new technologies for carbon emissions reduction. This concept increases energy consumption when a more efficient technology is introduced because of behavioural responses that diminish the benefits (Walzberg et al., 2020). Salter et al. (2020) discussed this effect to show that retrofitting and replacing extant building stock would not necessarily reduce carbon emissions as expected.

Table 5 outlines the intervention studies relating to energy.

Table 5: Energy intervention studies

Title	Author, date, & location	Intervention	Co-benefits
Sustainable buildings for healthier cities: Assessing the co-benefits of green buildings in Japan	Balaban et al. (2017), Japan	Energy-efficient green buildings.	Health: The green buildings were found to help prevent a range of health issues e.g., respiratory illnesses. Liveability: The green buildings provided a better indoor environment for occupants and reduced the amount of heat emitted. Resource savings: The green buildings reduced the energy required for heating and cooling.
Impact of co-benefits on the assessment of energy related building renovation with a nearly zero-energy target	Ferreira et al. (2017), multiple locations (Austria, Czech Republic, Denmark, Portugal, Spain, & Sweden)	Energy-efficient building renovations.	Liveability: The building renovations improved the indoor air quality, reduced external noise, improved safety, and improved the building's aesthetics. Resource savings: The building renovations reduced the energy demand of the buildings.
Temporal analysis of the material flows and embodied greenhouse gas emissions of a neighbourhood building stock	Lausselet et al. (2021), Norway	Energy-efficient building renovations.	Resource savings: The building renovations reduced the energy demand of the buildings, and ongoing maintenance costs due to the use of more durable materials.

Energy savings, emission reductions, and health co-benefits of the green building movement	MacNaughton et al. (2018), multiple locations (United States, China, India, Brazil, Germany, and Turkey)	Energy-efficient green buildings.	Health: The green buildings were found to help prevent a range of health issues e.g., respiratory illnesses. Air quality: The green buildings reduced the amount of particulate matter emitted. Resource savings: The green buildings reduced the energy required for heating and cooling.
Study of the Improvement on Energy Efficiency for a Building in the Mediterranean Area by the Installation of a Green Roof System	Peñalvo-López et al. (2020), Spain	The installation of a green roof on a public building (in the form of a rooftop garden).	Resource savings: Green roofs reduce the building's energy demand for heating and cooling.
Impacts of Urban Water Conservation Strategies on Energy, Greenhouse Gas Emissions, and Health: Southern California as a Case Study	Sokolow et al. (2016), California, United States	Water/energy conservation strategies, including expanding the use of recycled water.	Resource savings: The expanded use of recycled water was associated with energy savings.
Citizen Participation in Low-Carbon Energy Systems: Energy Communities and Its Impact on the Electricity Demand on Neighbourhood and National Level	Zwickl-Bernhard et al. (2021), multiple locations (Iberian Peninsula, Norway, & Austria)	Residential energy management strategies.	Resource savings: The energy communities contributed to energy savings through grid flexibility and energy demand.

Construction and 'smart' technologies

How buildings are constructed, and better use of technology has been identified as a way to reduce emissions and provide many benefits. Smart Home Energy Management Systems in buildings can help reduce grid-related energy consumption through coordination (Etedadi Aliabadi et al., 2021). In addition, smart neighbourhoods can provide better energy flexibility by managing their energy profile which is important in future power systems (Shafiullah et al., 2017). Smart technology can also have effects on urban design through communication and transportation. Al-Thani (2018) described several ways in which improvements using smart technologies can potentially help the environmental and social sustainability of neighbourhoods. Improvements include intelligent transportation systems such as better traffic management, providing better public transport or alternatives ways of transportation, intelligent communication system e.g., smart grids and smart meters, connecting public services with consumers, increasing safety and security, and increasing the efficiency of resources. Smart technologies can also accentuate the concept of multi-centric cities as a sustainable model (Al-Thani et al., 2018).

Balaban & de Oliveira (2017)* studied the impact of constructing buildings to meet green certification requirements in Tokyo and Yokohama, Japan. They conducted semi-structured interviews with owners, managers, and designers of new and sustainability renovated office buildings, as well as academic experts and city officials involved with the certification. The office buildings included in the study were all found to yield benefits in terms of energy and CO_2 reduction (along with associated cost savings). In addition, health benefits e.g., improved indoor air quality, improved thermal comfort, and less heat effects for pedestrians were also observed.

These findings were consistent with a study by MacNaughton et al. (2018)*, which looked at the benefits of green-certified buildings in several countries. They found that green-certified buildings saved energy, reduced illness, and improved air quality.

Lausselet et al. (2021)* investigated the impact of building material efficiency on GHG embodied emissions by modelling construction, renovation, and demolition activities over a 60-year time frame for the Norwegian zero-emission neighbourhood 'Ydalir'. They tested different strategies, finding that the use of the most efficient materials reduced GHG embodied emissions by up to 44%. Designing buildings in a way that allows for the re-use of elements and keeping up regular maintenance further reduced GHG embodied emissions by extending the lifespan of the building. Near-future emissions of the materials were identified as particularly important, as predicted technology improvements and the uncertainty of future activities meant that future emissions savings may not be realised. Salter et al. (2020)* conducted similar modelling research to analyse the impact of retrofitting and replacing existing buildings with emissions saving technologies and materials. They found that while this could achieve energy and emissions savings, the 'rebound effect' (where improved energy efficiency is counteracted by growing house sizes) meant that some of this benefit was lost. However, the infill redevelopment scenario decreased both energy and emissions per capita.

Table 6 outlines the intervention studies relating to construction and 'smart' technology.

Table 6: Construction and 'smart' technology intervention studies

Title	Author, date, & location	Intervention	Co-benefits
Sustainable buildings for healthier cities: Assessing the co-benefits of green buildings in Japan	Balaban et al. (2017), Japan	Energy-efficient green buildings.	Health: The green buildings were found to help prevent a range of health issues e.g., respiratory illnesses. Liveability: The green buildings provided a better indoor environment for occupants and reduced the amount of heat emitted. Resource savings: The green buildings reduced the energy required for heating and cooling.
Temporal analysis of the material flows and embodied greenhouse gas emissions of a neighbourhood building stock	Lausselet et al. (2021), Norway	Energy-efficient building renovations.	Resource savings: The building renovations reduced the energy demand of the buildings, and ongoing maintenance costs due to the use of more durable materials.
Energy savings, emission reductions, and health co-benefits of the green building movement	MacNaughton et al. (2018), multiple locations (United States, China, India, Brazil, Germany, and Turkey)	Energy-efficient green buildings.	Health: The green buildings were found to help prevent a range of health issues e.g., respiratory illnesses. Air quality: The green buildings reduced the amount of particulate matter emitted. Resource savings: The green buildings reduced the energy required for heating and cooling.
Iterative 'what-if' neighbourhood simulation: energy and emissions impacts	Salter et al. (2020), British Columbia, Canada	Different urban form patterns.	Resource savings: Infill development (compact houses) were found to use less energy than average-sized houses.

Water

Water and energy are interdependent in our neighbourhoods and cities. Energy is used for and can be generated from different water/wastewater dynamics. Energy generation also often requires water. Urban density and housing type can influence the water demand of the neighbourhood and, consequently, its energy requirements and carbon emissions. Dense neighbourhoods with lower water distribution needs and houses with less landscaping to be irrigated means a decrease in upstream energy consumption. However, less landscaping means less carbon sequestration, so there is a trade-off (Chhipi-Shrestha et al., 2017; Stoker et al., 2019).

Chang et al. (2017)* compared case studies of water reuse systems in South Korea. Their study investigated the energy consumption and GHG emissions of different systems to get an idea of how reuse systems compared to conventional water supplies. They differentiated between two types of systems: centralised and decentralised. Centralised systems are those where wastewater is treated in facilities using technology e.g., reverse osmosis, while decentralised systems are those that use a dispersed network of treatment methods including rainwater harvesting and greywater reuse. They found that centralised systems had both higher levels of energy use and greenhouse gas emissions compared to conventional water supplies. Meanwhile, decentralised systems were found to have roughly comparable energy use to conventional water supplies, but lower GHG emissions. They concluded that decentralised systems are the key to energy-efficient water management with minimal emissions (Chang et al., 2017)*****.

The reuse of water as a climate-friendly strategy was also studied in the HIA done by Sokolow et al. (2016)*. They evaluated several different water conservation strategies for cities in Southern California, finding that the expanded use of recycled water was the most promising option, with decreases in total water consumption, energy use, and greenhouse gas emissions.

Alves et al.'s (2019)* comparative case studies investigated the effects of various flood management strategies, including green roofs, rainwater barrels, and pervious pavements. A reduction in CO_2 emissions was identified as a benefit of each of the flood management strategies, mostly attributed to less need for fossil fuels due to the lower energy use of these strategies compared to standard stormwater measures. Along with better rainfall run-off management, green roofs also provided carbon sequestration, air filtering, and cooling. helped reduce air pollution through the filtering of air particulates, as well as keep buildings cooler, reducing the need for other forms of cooling such as air conditioners. Rainwater barrels helped reduce demand for water by enabling the collection of run-off locally, while pervious pavements helped cool surrounding outdoor areas.

Table 7 outlines the intervention studies relating to water.

Table 7: Water intervention studies

Title	Author, date, & location	Intervention	Co-benefits
Assessing the co-benefits of green-blue-grey infrastructure for sustainable urban flood risk management	Alves et al. (2019), Sint Maarten Island	Green-blue-grey water management infrastructure.	Liveability: Pervious pavements helped cool surrounding areas. Green roofs helped keep buildings cool. Air quality: Green roofs helped reduce air pollution through the filtering of air particles. Resource savings: Rainwater barrels helped reduced demand for water by enabling the collection of run-off locally.
Energy consumptions and associated greenhouse gas emissions in operation phases of urban water reuse systems in Korea	Chang et al. (2017), South Korea	Urban water reuse systems, including greywater reuse systems.	Resource savings: When factoring in the environmental benefits, greywater reuse systems had energy savings compared to conventional systems.
Impacts of Urban Water Conservation Strategies on Energy, Greenhouse Gas Emissions, and Health: Southern California as a Case Study	Sokolow et al. (2016), California, United States	Water/energy conservation strategies, including expanding the use of recycled water.	Resource savings: The expanded use of recycled water was associated with energy savings.

Literature review key findings

While limited in number, the above review of intervention-based evidence supports the idea that efforts to reduce emissions through urban form can result in numerous co-benefits for communities.

Intervention domains

Interventions were grouped into six domains. They were often overlapping with interventions associated with multiple domains and co-benefits. In summary:

- Urban greening was associated with emissions reduction and co-benefits through carbon sequestration, air filtering, ecosystem services, urban cooling, and human health benefits. Interventions included:
    - Greenways
    - Urban gardens (including community food gardens)
    - Green rooftops
- Urban form has long established pathways with mobility behaviours and wellbeing benefits, however, interventions in urban form tend to be complex, harder to evaluate, and impacts take time to be observed. Emissions reduction associated with denser and/or more liveable urban form was through:
    - Reduced household energy consumption.
    - Increased active transport and associated mental and physical health benefits.
- Mobility and transportation were associated with emissions reduction primarily through shifts to low carbon transport modes. Co-benefits included improved air quality and human health. Interventions through neighbourhood to city planning were primarily:

  - Mode shift through increased infrastructure and services for active and public transport.
  - Compact urban form (street connectivity, land use mix).

- Energy interventions were primarily focused on emissions reduction through shifting to lower carbon fuels and reduced consumption. Fuel shifting was associated with improved air quality (and health benefits). Energy reduction (and emissions and co-benefits) was achieved through interventions such as:

  - Greening, which reduced energy consumption to heat and cool urban environments.
  - Sustainable 'green' building forms reducing energy consumption and improved urban environmental qualities.
  - Compact urban form requiring less energy consumption and improved liveability.

- Construction and 'smart' technologies offered emissions reduction through greater energy and materials efficiency across infrastructure and within buildings. Examples included:

  - Greater energy efficiency through more sustainable 'green' management of buildings and increasing the compactness of urban form through infill housing which also provided improved liveability.
  - Reducing embodied emissions in urban housing development by taking a 'whole of life' approach to construction.

- Water and energy were interdependent in urban settings. Reductions and efficiencies in water use were associated with reduced emissions through lower energy use. Interventions primarily focused on:

  - Recycling water to reduce energy consumption.
  - Stormwater and rainfall runoff, for example through greening which also provided air quality and health benefits.

Co-benefits

A wide range of co-benefits associated with emissions reduction were identified in the literature. They included:

- Greater affordability through reductions in resource use (for example, lower energy required to operate wastewater systems).
- Liveability improvements (for example, through greening of urban environments).
- Improved health outcomes (for example, increased physical activity levels and associated reduction in disease).
- Improved air quality (for example, through reductions in vehicle traffic).

Applicability

The interventions came from across the globe; however, most came from the northern hemisphere. While all could be applied in Aotearoa New Zealand, some were more relevant to areas with compact urban form and/or where mode shift investment could be made.

Methods

The scale of interventions varied from micro (buildings and neighbourhoods) to macro (cities and regions). Macro-scale interventions included 'horizontal' infrastructure such as wastewater and city-wide walking and cycling networks. Micro-scale examples include green roofs and heating systems. Some interventions were focused on one aspect of urban form, such as building materials, whereas others, such as neighbourhood regeneration, were more wholistic and encompassed multiple scales, types of interventions, and benefits.

The methods used to evaluate and report interventions was similarly varied. Some were descriptive assessments of a single case, others used multiple methods (such as HIA's). The evidence base represents a mix of qualitative and quantitative data and analysis methods. The most common method in the interventions we have reported on was case study comparisons. As well as observational studies, modelling methods were used to estimate the likely or possible effects of changes to urban form on emissions and/or co-benefits. We found no case control or cohort studies and only one experimental study that met our criteria (Chapman et al., 2018). While there are intervention studies that use these high-quality methods to improve the validity of findings (such as Aldred and Goodman (2020) and Hosking (2022)), they had (yet) not assessed the effect of the intervention on emissions.

4 Practice reviews

To complement the findings from the previous research stages, four opportunistic practice reviews were carried out to identify industry lessons for the successful implementation of interventions. Interviews were held with WSP practitioners to discuss projects they had been involved with, including what has worked, what has not worked, and how barriers have been addressed.

As well as wanting to understand which changes in urban environments can lead to emissions reduction and community benefits, we wanted to understand more about how knowledge and evidence can best be used to bring about change. We sought lessons from industry about the role played by knowledge and evidence in the successful implementation of change at neighbourhood to city scales, particularly when the changes were novel and established evidence was therefore limited. The following cases are based on the experiences of four projects seeking to reduce emissions and deliver community benefits through changes to urban form. The cases are described below in terms of their goals and benefits to communities, followed by how knowledge and evidence were used to achieve outcomes. Next, the key themes emerging from across the cases are discussed. And finally, combined lessons identified from the analysis of all cases studies are noted.

1: Holistic placemaking at Southampton Ring Road — United Kingdom

The goal of the project was to create better places for people to live by increasing active and public transport modes and removing cars from the central city in Southampton, UK. This was achieved through improvements to the Inner Ring Road.

Figure 5: Pedestrian installation in the Northern Ring Road[3]

Governance and strategy

The project was a response to national and local drivers. The wider national context was that the British Government aimed to reduce carbon and encourage economic growth. The project was supported by the Transforming Cities Fund to fill the gaps in the local areas and cities that do not have sufficient funds for Net Zero policies. At a local level, the city council wanted a pro-cycling city, and less congestion and air pollution. Central government provided the overall policy context and funding while the city council managed the roads.

[3] https://www.dailyecho.co.uk/news/19029618.plans-unveiled-4-5m-southampton-city-centre-ring-road/

The key players identified included the transport department, city council, British Government, residents and visitors, businesses, public transport providers, cyclist forums, and tourism infrastructure providers (Southampton has the United Kingdom's largest cruise ship terminal).

Process

Evidence and knowledge came from many sources and included the gathering and analysis of data, modelling, technical expertise and experience across multiple disciplines, and local knowledge. Evidence came from analysis of traffic modelling and traffic data, public transport data, and emissions and air quality data came from monitoring units in the city. Multi- or cross-disciplinary knowledge came from the inclusion of multiple technical specialists working together, including specialists in traffic signals, environment, sustainability, active transport, landscape, and design standards.

Gaining confidence in the knowledge available was achieved in several activities and ways of working, including having a multidisciplinary team, running internal and external workshops, holding a brainstorming session to create a long list of ideas, and letting people voice their ideas even if it was not their discipline. Having everyone around the table helped bring new ideas, push what was 'normal', and explore novel ideas, even if they did not come about. Close collaboration across all parties throughout the project and being on the same page about net zero carbon goals helped with team confidence and project success.

Challenges

Because design is changing in the UK and around the world by moving towards sustainable modes, there were not always established design standards for what was done. To address the knowledge gap, the team called on the very strong local knowledge element, previous experience with other projects, and different designs; and consulted with people who had a deep understanding of design standards. The team included people who had been involved in policymaking, and as there were always interpretations needed, it was helpful to talk to them to understand what the standards intended. Local knowledge was highly valued by the client and the project team who were located close to the site.

Benefits

Beside emissions reduction, the benefits of the project included encouraging economic growth through a more attractive retail and business environment. Social benefits included enhancing the living environment to attract residents and visitors, as well as improving overall quality of life.

2: Reducing emissions through funding mode shift activities — Aotearoa New Zealand

Enabling emissions reduction through transport mode shift has been a priority for Aotearoa central and local authorities. The release of Te Manatū Waka Ministry of Transport's Government Policy Statement (GPS) on land transport in 2018 signalled a shift in the prioritisation and allocation of transport funding, with a greater portion allocated for mode shift promoting activities (e.g., walking, cycling, and public transport projects). These changes also aligned with other work in the transport and sustainability space e.g., Te Manatū Waka's Transport Outcomes Framework (see Figure 6), which includes an environmental sustainability component with a focus on transitioning to net zero emissions. Requests for funding from the National Land Transport Fund (NLTF) are highly contested and typically require robust evidence supporting the prioritisation of business cases — which is crucial for almost all projects, particularly those of significant value.

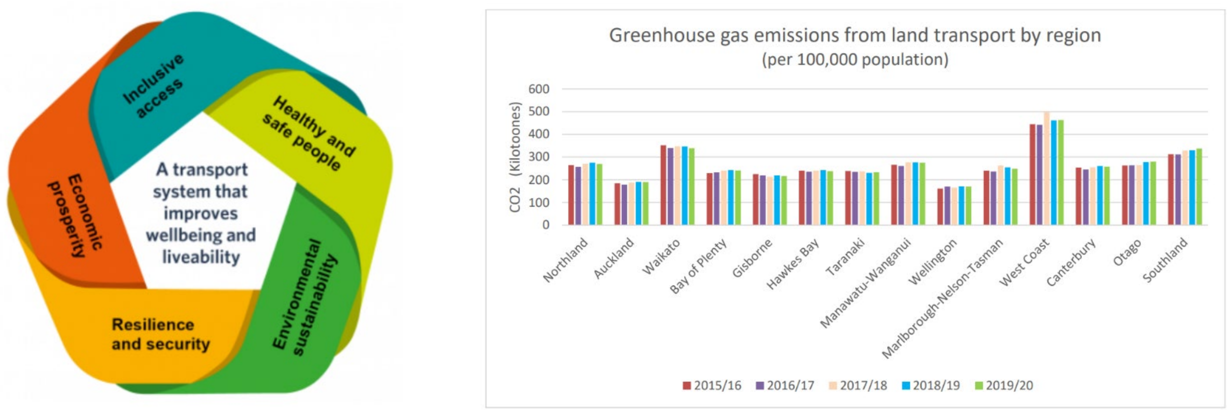

Figure 6: Government Transport Outcomes Framework (left) and Greenhouse gas emissions from land transport by region (right)[4]

Process

As part of recent work undertaken to assess the impact of the changes in GPS 2018 on mode shift, ten interviews were held with staff from regional councils, local councils, and Waka Kotahi. During these interviews time was spent discussing the importance of evidence in the prioritisation and decision-making process, both to ensure good outcomes for projects and to give them the best chance of funding approval. The staff interviewed came from councils across a range of scales — from large urban areas (e.g., Tāmaki Makaurau Auckland and Te Whanganui-a-Tara Wellington) to smaller, more rural areas (e.g., Northland and Ōtākou Otago) (Te Manatū Waka, 2022).

Challenges

Many interviewees spoke about how areas with larger urban centres were more able to access robust, useful evidence to support applications for mode shift promoting projects. They identified that this was in part due to their larger budgets, meaning they could more easily afford to generate their own evidence through travel surveys, pedestrian and cyclist counts, and demand modelling. The evidence that they were able to include in their business cases therefore tended to be more thorough compared to less well-resourced smaller councils. Another factor that several participants mentioned was how larger councils tended to have a longer track record in the mode shift space. They often had walking, cycling, and public transport networks that were more complete than those in smaller urban areas, as well as staff with more experience working on such projects. Again, this meant they had more opportunity to collect data and build an evidence base to support future projects.

Several interviewees noted that regardless of the size of the urban area, all councils usually relied on national datasets in some form. Generally, national datasets were preferred to local datasets as this allows for greater consistency across regions, which was important when prioritising national funds and needs. Two common examples included commute data from the Census (journey to work and journey to education), and more detailed travel data from the 'New Zealand Household Travel Survey'. These datasets were typically used whenever mode share evidence was required (provided they could be disaggregated at the appropriate scale). When this evidence was not sufficient, it was supplemented with locally collected evidence e.g., travel surveys or cordon counts (if affordable). National datasets were an invaluable resource for all councils, but particularly for smaller councils, who otherwise may not have the resources to collect data to fill gaps in the available evidence. This was highlighted by the interview participants from smaller

[4] Government Policy Statement on Land Transport 2018 Annual Report, 2022, p. 35

councils, showing the importance of useful, accessible, and reliable evidence for councils of all sizes and budgets to be able to support mode shift promoting projects.

Evidence has become much more important for Waka Kotahi too. Pressures on transport funding and changes in how projects were prioritised meant Waka Kotahi staff tasked with assessing projects increasingly relied on more thorough business cases which required a stronger evidence base for decisions. Often, this meant that the councils were being asked for additional evidence to support their projects, putting smaller councils with less access to evidence at a disadvantage. In addition, interviewees reported difficulties obtaining evidence for the type of interventions of sufficient scale and complexity needed to achieve substantive mode shift (e.g., larger network building projects developed over time and integrated with placemaking, travel behaviour change elements and land use). Instead, the process was seen as favouring established discrete, shorter term and smaller scale projects which were easier to assess within the prioritisation process.

Benefits

Across both councils and Waka Kotahi, many of the interviewees spoke of how the requirements around evidence have changed over time. In the past, demonstrating that a project was aligned with the relevant strategic direction was often sufficient to receive funding approval. In recent funding periods, however, evidence was at the core of almost all proposals. New technologies, e.g., smart sensors, were making it easier to build an evidence base — but currently the data collected is often siloed and not always available for others to use. Nationally driven data collection efforts help, but there is also significant value in local initiatives, particularly for assessing projects that have already been implemented. Greater coordination between councils and Waka Kotahi could make this evidence available more widely and help bridge the gap between those with plentiful evidence and those with little. Further, greater access to evidence could strengthen the quality of projects even at larger councils.

3: Tūrangawaewae Marae sealing project — Aotearoa New Zealand

The goal of the project was to seal the car park at the Tūrangawaewae Marae to provide parking and access for buses and vehicles during events and access to the kōhanga reo and surrounding papakāinga. After the site analysis identified that the site was near the Waikato Awa (river) and was prone to flooding, the project focus shifted to create a dual-purpose system that provided flood protection as well as water quality treatment. The vision of the Marae was to protect and enhance the mauri (life force) of the Waikato Awa through naturally filtering stormwater before entering the Awa — the goal was that water quality be much better than it was before the carpark was upgraded.

Figure 7: Tūrangawaewae Marae[5]

[5] https://www.nzia.co.nz/awards/national/award-detail/3804#!

Governance and strategy

The project involved Marae Trustees (client), an indigenous landscape architect (cultural advisor on behalf of Marae Trust), and a stormwater engineer, including Te Mana o Te Wai and Te Mana o Te Awa contractors.

Process

Knowledge and evidence were drawn from multiple sources e.g., mana whenua (local knowledge), technical knowledge from the indigenous landscape architect and stormwater engineer, and site analysis during the site visit to look at topography, microclimate, and blue and green networks.

Local knowledge provided a Te Ao Māori lens, such as having a holistic understanding of what contributes to the mauri (life force) of the Waikato Awa, understanding the intrinsic relationship that people have with te Awa, including sites of significance, sites where flooding occurs, and how the surrounding environment impacts and is impacted. Technical knowledge ensured that the project aligns with national policy e.g., Te Mana o Te Wai and Te Mana o Te Awa. It provided information on which common contaminants to look for, such as heavy metals, as well as empirical data to determine how much and what types of mulch and planting to use. Previous evidence provided knowledge of which best practices would be applicable in this environment.

The knowledge and evidence drawn from multiple sources allowed for an operations and maintenance plan that is embedded with Te Ao Māori while maintaining the technical and functional aspects of the system. Merging local knowledge and technical knowledge created a culture shift that designs for the future. This project was a catalyst that will inform future development across the Marae, as it is the first formal stormwater treatment on the Marae that utilises sustainable best practices. Regular communication, consultation, and partnership fostered a sense of ownership, and the Marae are set up to look after it for the device's lifecycle.

Challenges

The masterplan that was developed prior to designing this project helped prepare for the future by allowing for retrofitting through staging (i.e., based on budget). The key aim was to do what they could with the resources available — focusing on the quick big wins ensured the carpark contributed to the protection and enhancement of the Waikato Awa. The stormwater solution was consistent in keeping with the strategy but when it came down to construction, it was not completed correctly by the contractor, resulting in the stormwater engineer having to regularly monitor and keep things in check. Monitoring ensured the contractor fulfilled the vision of the Marae.

Benefits

The project alleviated flooding issues as the site is adjacent to the Waikato Awa and has a natural spring beneath it. This system provides multiple layers of benefits such as:

- Improving water quality prior to it entering the Waikato Awa using native vegetation, mulch, and gravel.
- A natural greenway using a daylighting system versus a traditional grey sealed car park
- Increased habitat for biodiversity.
- A carbon sink for runoff.
- A safe and educational tool that people can visually see which encourages them to look after it — ultimately showcasing an increase in health and wellbeing of the Waikato Awa.

Another key benefit of this project is future proofing so that it can be retrofitted when funding is available to the Marae. The masterplan was prepared by the Indigenous Landscape Architect who provided a holistic overview of stormwater and water across the whole Marae. This gave the stormwater engineer insight into future opportunities, so when redirecting filtered water towards the Waikato Awa, the design was able to incorporate piping that could be retrofitted in the future, as it is at an adequate depth for raingardens. The Marae Trustees said they had major flooding issues during the site visit, therefore in alignment with the masterplan, staging provided immediate remediation by implementing the carpark while staging to allow for future development. The stormwater engineer was also able to communicate to the contractor and regularly monitor to ensure the contractor was building it correctly.

Being considerate of the Marae's resources and budget alleviated pressures by understanding the site as a whole and how the sealing project could contribute to the larger picture. Marae do not always have money to fund large scale interventions or the space, therefore having evidence to understand how much water needs to be filtrated can determine raingarden footprints. Evidence showed that smaller raingardens are cheaper and perform well because they are small and have fewer plants which allows for larger garden spaces so larger trees can be planted to sequester more carbon.

4: Aiming for net zero climate adaptation: Finding extra stormwater detention capacity — Copenhagen

The goal of the project was to increase capacity to cope with future extreme cloudburst events in a net zero way. In 2011, Copenhagen experienced a severe cloudburst event resulting in extensive damage to building and homes. It was described by the practitioner as 'pure chaos'. Because of the unexpected nature of the event, it was seen as an indicator of what was to come with climate change. The national response has been to go 'full engineer' on the problem by increasing water retention capacity by 10,000m^3 to cope with extreme events in the future, typically through established 'box and culvert' type solutions. For example, there are around twenty cloudburst retention tunnels built with tunnelling machines ten to twenty metres below the surface which from an embodied carbon perspective is 'hopeless'. However, the approach results in a lot of additional carbon being emitted in the construction of extra capacity ahead of when the capacity will be needed.

Denmark has a strong, mandated commitment to carbon reduction and biodiversity that influences decisions. There is a relatively new climate law to reduce emissions by 70% from the 1990 baseline. The current focus has been on operational carbon (e.g., energy consumption during operation), rather than embodied carbon (e.g., from construction).

Initially, the role was to provide detailed designs as earlier design stages determined what was needed. However, as it was in an area with high nature values, there was an opportunity to consider where that additional capacity should be. The area in question was (unusually for Denmark) previously undisturbed, low-lying land with a stream and with high biodiversity values. These factors provided the opportunity to increase capacity through both sub-surface and on-surface means, using natural structures. This would mean enhancing the environmental qualities of the area, rather than just adding grasslands.

Process

'The Wheel' is a systematic approach to reducing carbon in climate adaptation and construction that poses challenges at their strategy, planning, design, and construction phases. It asks whether there are alternative approaches to describing and addressing the problem and achieving desired goals — in this case providing extra stormwater capacity and achieving low whole life carbon (operational and embodied carbon over the whole life cycle). Using an LCA methodology, the carbon costs per cubic meter were calculated, showing that the stormwater pond option was 200 times lower than the traditional concrete pipe solution. Other options explored included reducing the paved surfaces (and associated runoff) through urban regeneration and water sensitive design; working with communities to gain acceptance of surface water at greater frequency and allow flooding in some areas. Given the usual focus on operational carbon, the Wheel helped change the conversation. Bringing in data and discussions about embodied carbon led to 'aha' moments about how to increase cloudburst capacity without adding to carbon emissions.

For example, options for increasing capacity to manage stormwater could include in-ground concrete or plastic pipes, 'green' roads with rainfall gardens, or downpipe enhancements that in extreme events will channel excess water away from buildings and the stormwater system to nearby surfaces (or ideally, to ponds) to be absorbed once the cloudburst is over. Each of the options has the same capacity, but with the latter two have considerably less embodied carbon.

'The Wheel tool also facilitates conversations about the social, environmental, and economic benefits and drawbacks, alongside climate adaptation and carbon reduction. For example, the downpipe option would be far cheaper than the other two, reducing the economic burden for being resilient in the future on communities and councils, and allowing limited funds to be spent on other services. By taking solutions above surface and including nature, the project can contribute a lot more than an in-ground solution.

Challenges

The challenge towards reducing the carbon burden of increasing cloudburst resilience is that there are already established plans and practices for increasing capacity — the 'full engineer' model. People will naturally be reluctant to step back from those plans and established ways of doing things, especially under pressure when the tendency is to fall back on existing solutions.

> *"The major concern is that people tend to just solve the problem rather than giving themselves time to re-think what is causing the problem" (interviewee quote).*

Another challenge is that the Wheel approach challenges the technical expertise of engineers and/or other disciplines to do things differently. It can be difficult because they see their established solutions as doing good climate adaptation. But when they are challenged to bring their technical expertise and experience to the new problem of addressing embodied carbon, they get on board. Rather than teaching people how to calculate carbon, the team have learnt it is more productive to give people the capacity and motivation to solve the problem in their own way. As described by the interviewee, their identity as experts is retained, not challenged.

> *"they... use their old knowledge in the new context and once they start that, they are still the experts"*

Once people are aware of the embodied carbon problem, they tend to figure out solutions. But it's not about changing things completely, it's about providing enough data to work with and act on. It's the same whether it is the community or technical experts, they all want to contribute to a better place. Carbon reduction is extremely purpose driven.

Information and evidence play an important role in gaining buy-in to both the problem and the solutions. Denmark uses the Cloud Atlas based on IPCC data to model cloudbursts, which is regarded as authoritative data nationally and within the stormwater community to determine the level of risk. People trust the Cloud Atlas to add in climate change factors into normal calculations to be sure that future cloud bursts events will be dealt with within existing infrastructure.

Gathering evidence to calculate whole life carbon can be challenging. A start has been made on developing baselines on projects and LCAs calculate whole life carbon. It will help people to see the impact of different types of solutions to the same problem and ascertain which will be the best solution from a carbon perspective. The team have found that it does not need to be complex, it can be simple as a starting point. Because it is new, there is an acceptance that data will not be completely accurate for a few years. But they have found that limited data must only be accurate enough to act on.

Benefits

Introducing carbon reduction goals has led to a shift in what is considered a 'good' solution. The project reflects the broader sustainability approach that aligns with Denmark's support for the Sustainability Development Goals. It means that if the project supports biodiversity, economic, and social goals, then 'we don't have to argue that much'. Being able to communicate the biodiversity and carbon benefits is usually enough to get people involved. Also valuable is being able to tell a story of how a project will help meet legal requirements to reduce carbon and mitigate emissions. While the current focus is on carbon and biodiversity, there is also awareness of the need to address mental health in the community. Nature-based solutions to climate change and biodiversity are recognised as addressing mental health — so there is the potential that all these future problems would all be addressed with 'good' solutions.

Practice review thematic analysis

Three themes emerged from the cases — connecting, valuing different ways of knowing, and generating knowledge.

Connecting

Connecting between key players enabled success. In the Southampton case, while central government and the city had the same goal of reducing emissions, the Transforming Cities Fund provided the means to connect the two. Strong connections between those delivering the intervention and council meant everyone was invested in the project outcomes. Recognising the importance of connections with the council and other stakeholders (e.g., residents, businesses, transport providers) enabled a collaborative approach over the course of the project.

In the Funding Mode Shift case, national datasets provided valuable connections between local, regional, and national authorities. They allowed useful comparisons when prioritising funding and reduced the burden of evidence-generation on smaller councils.

The Tūrangawaewae Sealing case connected recent changes to national policy (Te Mana o Te Wai and Te Mana o Te Awa) to what was initially a small resealing project through master planning. The masterplan showed the water runoff connections across the entire Marae and not just between the carpark and the river. This holistic approach ensured the stormwater within the carpark could be managed immediately without causing further flooding issues where natural springs were present. The project benefits of water quality and flood risk mitigation were connected in the project to other benefits that were also important to the Marae — health, safety for tamariki, and educating people about the health of te Awa and environment, native biodiversity, and potentially, the benefits of wharekai as a food source for the marae

The rain gardens were seen as a valuable way of connecting people to the environment as they provide a very visual illustration of the lifecycle of rainwater, planting, and rubbish. It also provides a habitat for native biodiversity, so when there are birds and insects thriving in these areas, people will see that there is life.

For the Copenhagen stormwater capacity project, the Wheel and the LCA carbon calculations connected technical experts and clients with the carbon problem and new ways of thinking. The process facilitated conversations that moved thinking beyond the traditional solution of pipes, towards the opportunity to make the connection between increasing stormwater capacity and enhancing the biodiversity of the site through ponds and wetlands.

Valuing different ways of knowing

The cases called on and valued many ways of knowing, over and above traditional technical knowledge and evidence. In the Southampton case, the importance of local knowledge was recognised and where needed, complemented with expertise from further afield. Recognising the complexity of the project, the specialist knowledge from multiple disciplines was valued and so deepened the understanding of the issues and way forward. Because the project was relatively novel, not everything was underpinned by robust evidence or best practice. The uncertainty was managed by calling on the wisdom and insights of people who could translate experience-based knowledge and principles (e.g., of how design standards were developed) in new ways. Knowledge from across the council (not just the department directly involved) and stakeholders contributed to the project, increasing confidence for the whole team.

Valuing different ways of knowing may be more challenging when funding is under pressure and/or when priorities are being determined across multiple organisations. In comparison to the Southampton case where gaps in the formal evidence base were able to be filled with expertise and experience, the Funding Mode Shift case seemed to give higher priority to the kinds of formal evidence used to support a business case. For example, national datasets were talked about as being preferred because of their consistency and reliability. For smaller authorities less able to fund their own local data collection, national datasets also offered affordability and availability. On the other hand, having experienced staff on board was also recognised as an advantage.

In the Tūrangawaewae Sealing case, pressures came from the Marae's restricted budget and traditional sealing and stormwater engineering practices. While initially conceived as a stormwater engineering project, indigenous landscape architecture knowledge was also valued to ensure the project met the needs of the Marae and te Awa. The holistic nature of the masterplan provided an overview of where water was emerging due to the site being on natural springs, and where it was going across the entire Marae before existing into te Awa. The masterplan articulated what was known and what mattered most to the Marae, which was then incorporated into how the project developed and planned for retrofitting in the future. Drawing on local knowledge from Mana Whenua, particularly those who look after the Marae, provided unique insight into which areas are most prone to flooding. Knowledge and perspectives from Te Mana o Te Wai, Te Mana o Te Awa, and Te Ao Māori determined what was built and how it was done.

Existing technical knowledge and experience was valuable for coming up with alternative solutions and innovations for low carbon stormwater solutions. Posing embodied carbon as just another problem engaged engineers to apply their problem-solving skills and technical expertise, rather than dismissing their relevance. By bringing fresh eyes to the problem, the Wheel process also encouraged different priorities and knowledge (e.g., biodiversity) to be included in design solutions and decisions.

Generating knowledge

All cases were challenged by limited data and evidence about the problems and options. Their response was to seek out and gather new, relevant data, and/or to take knowledge from related work and translate it into new knowledge. Useful knowledge and evidence were generated through several key avenues in the Southampton case. Data was available through ongoing monitoring of the environment (e.g., air quality) and behaviours within it (e.g., bus passengers). Results from the analysis and modelling generated local evidence to guide decisions. Value was placed on knowledge and insights accumulated in previous projects were shared, which helped provide confidence in decisions The project provided freedom to explore, share, and voice ideas — expanding beyond disciplinary boundaries or the role played by people within the project. The approach of having everyone 'around the table' meant new ideas could be explored, contributing to the greater understanding of perspective, goals, and needs, as well as helping achieve buy-in and confidence.

In the Funding Mode Shift case, the capacity to accumulate evidence over time and across projects was seen as an advantage of urban areas with a longer history and greater networks of mode shift promoting activities, as well as greater capacity to generate knowledge. The limited ability of smaller authorities to generate local data and address gaps was seen as a barrier to obtaining national support for funding emissions reducing mode shift, as well as making it harder to make the case for change with local communities.

The Tūrangawaewae Sealing project recognised that there was no standard practice for monitoring the effectiveness of the rain gardens on outcomes or delivering benefits beyond the standard operations and maintenance plans. However, the increased visibility and awareness from the daylighting of water offers the possibility of new knowledge and monitoring of the environment by people that could be incorporated into reporting. By listening to the Marae at the scoping stage, local knowledge of flooding and water quality problems were included in the masterplan. Because of that conversation, new knowledge about planting, runoff, and Te Ao Māori was able to be generated into the plan.

Learning over the course of the project generated new knowledge. Achieving the desired outcomes was helped by close communication of what was important (so that the right soil was used in the rain garden) and monitoring how the work was being undertaken. New knowledge was also generated through the experience of optimising planting to achieve the best carbon outcomes that can be taken forward into new projects and developments.

Data and evidence are often unavailable due to the addition of carbon reduction to project goals, along with the challenge to find novel ways of delivering stormwater solutions. Rather than continue with standard practices in response, the stormwater team took a step back and invested in generating a baseline that can be referenced for future projects. In the meantime, fit-for-purpose knowledge can be generated — while data on carbon assessments is limited, it only needs to be accurate enough to see a difference between options — i.e., accurate enough to act.

Practice review lessons

The following three lessons for creating a useful evidence base were identified:

1. Knowledge is gained through connection – across ideas, experiences, perspectives, and people. Learn from others and the work done on previous projects to accumulate and translate knowledge.
2. Value and combine different forms of knowledge, especially when trying something new. Complement existing evidence with experience, expertise, multiple disciplines, and different perspectives.
3. Accept that knowledge is incomplete and consider:
   - How gaps can be filled through applying expertise and experience differently.
   - How much accuracy is needed to act.

5 Finding meaningful evidence — commentary

Finding meaningful evidence for interventions that can reduce emissions through changes to urban form in ways that also provide community co-benefits has proved to be challenging. While there is a reasonable amount of information on the mechanisms for change, actual evidence of interventions and what would be effective in Aotearoa New Zealand is limited. We found a total of 20 papers. Other reviews of similarly complex topics have also had a similar result, particularly those taking a rigorous systematic review methodology. For example, Panter et al. (2019) systematically reviewed studies to ask whether interventions to the physical environment led to more walking and cycling. While the overall conclusion was that interventions addressing accessibility and safety were the most effective at promoting walking and cycling, they found significant shortfalls in the evidence. Of the 13 papers included most were of relatively poor research quality and contained little of the contextual information required to understand whether an intervention could be successfully applied elsewhere.

This review was guided by the needs of those charged with making decisions about our neighbourhoods, towns, and cities, rather than an academic question. We have found a significant mismatch between what decision-makers have told us they want from evidence and what is available. This is not unexpected, however and is referred to by Albris et al (2020) as the 'epistemological gap' between the development of a knowledge base and how it is to be used:

> *"While the output of scientific research is (ideally, at least) a nuanced recommendation based on probabilities and careful consideration of uncertainties, decision-makers are forced to follow a Boolean, binary logic when selecting policy options" (Albris et al., 2020, p. 7).*

Are there other ways of thinking about evidence in the case of complex interventions? As seen above, the standard systematic literature review approach all too often ends up with a small number of studies that are not easily comparable or transferable to real world settings.

Two approaches from public health and health promotion researchers provide a more nuanced, practical approach to knowledge generation and are discussed briefly below. Tannahill (2008) argued that a reliance on traditional evidence hierarchy criteria limits what evidence is available for assessment and what meaning can be taken from them. For example, while randomised controlled trials are the most methodologically robust study design, they are known to be hard to transfer to real world settings, limiting their effectiveness, particularly interventions that address complex environments. Alongside other points made by Tannahill, two stand out as relevant lessons here:

- *"…the impossibility of securing all the evidence we would like to have to inform action makes it reasonable to use plausible theory, weighed up alongside available evidence, in health improvement decision-making. If decisions were only to be based on available strong evidence of effective actions, the result would often be a very small number and range of actions, with a risk of achieving less population health gain and less of an impact on health inequalities than would be achieved through a fuller set of measures devised on the basis of theoretical plausibility as well as evidence of effectiveness…"*
- *[and]"…comprehensive packages of actions can generally be expected to have more impact on population health than a narrower approach, but available effectiveness evidence largely relates to single interventions evaluated in isolation and does not shed enough light on the extent to which particular policies or other actions (even including some that appear ineffective when looked at in isolation) might have an impact when used in combination."* (Tannahill, 2008, p. 385)

Tannahill (2008) proposed that what counts as 'effective' should incorporate theory and ethics, alongside methodological strength, illustrated in the decision-making triangle below (Figure 8).

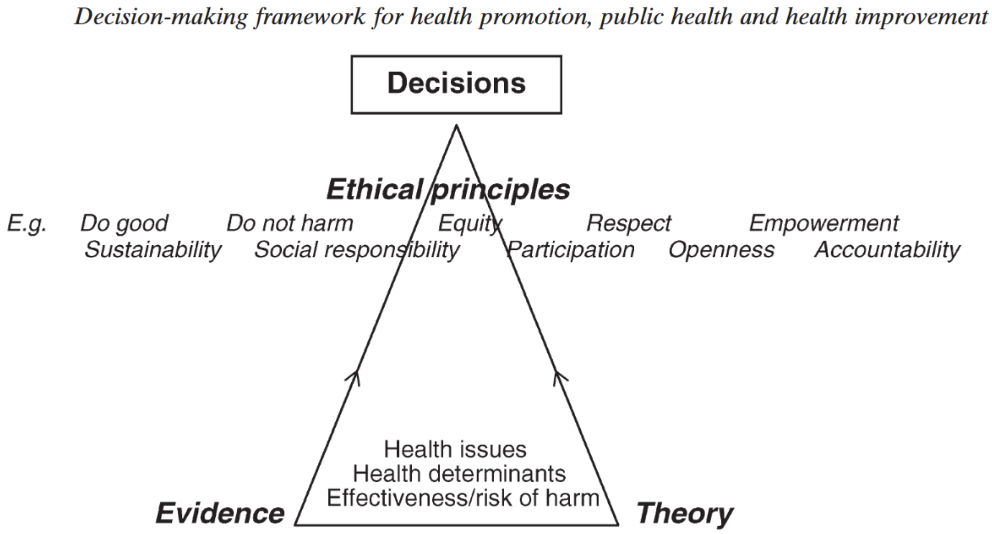

Figure 8: The health improvement decision-making triangle[6]

A second, 'mosaic' approach seeks to capture the synergies between different forms of evidence to better inform practitioners. Ogilvie, Adams, et al.'s (2020) work on natural experiment evaluations identified important lessons for the emissions reduction challenge. They focused on 'primordial' interventions, i.e., ones that seek to eliminate health risk factors, because they operate at the population level by attempting to change the underlying environments which shape behavioural patterns. Broader-reaching, population-focused interventions, e.g., urban regeneration, will typically have smaller effect sizes than targeted interventions but have the potential for greater impact as more people are affected.

However, natural experiments of primordial interventions do not fit readily within the traditional research-to-practice model (also referred to as 'evidence-based practice') (Ogilvie, Adams, et al., 2020). They propose that 'practice-based evidence' also needs to be generated, where evidence of effectiveness emerges from the multiple cases or actions that arise as changes are made in real life. Both pathways for generating and using evidence can work together (Figure 8). The authors put forward three implications for supporting primordial interventions through a more effective and useful evidence base:

1 Reducing critical uncertainties through accumulated knowledge (rather than definitive, hypothesis testing)
2 Including non-randomised study designs where they address the principles of a Randomised Control Trial (RTC) (i.e., to reduce confounding), ensuring relevance to the real-world setting, and establishing plausibility of causal inference
3 Thoughtful appraisal of how useful the evidence is, including consideration of internal validity (Ogilvie, Adams, et al., 2020)

[6] Tannahill (2008) p. 387

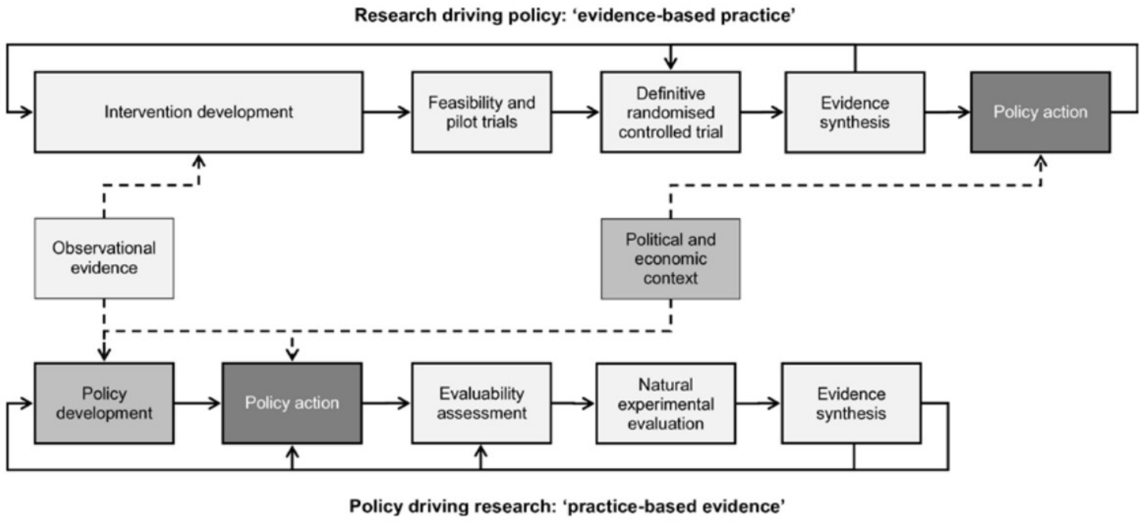

Figure 9: Two complementary modes of evidence generation[7]

Ogilvie, Bauman, et al. (2020) went on to describe the need for a 'mosaic' approach to developing an evidence base of interventions, arguing that:

> *"…if conventional evidence synthesis can be thought of as analogous to building a wall, then we can increase the supply of bricks (the number of studies), their similarity (statistical commensurability) or the strength of the mortar (the statistical methods for holding them together). However, many contemporary public health challenges seem akin to herding sheep in mountainous terrain, where ordinary walls are of limited use and a more flexible way of combining dissimilar stones (pieces of evidence) may be required."* (Ogilvie, Bauman, et al., 2020, p. abstract)

The 'mosaic' approach to evidence synthesis proposes three principles:

1 *Looking beyond interventions.* Rather than focusing on the form of the intervention, they recommend considering the functions "…the processes and changes they provoke…" (Ogilvie, Bauman et al. 2020, p. 6), that could be achieved in different ways, in different places.

2 *Searching for patterns.* Rather than seeking causal estimation from single studies, they suggest triangulating quantitative and qualitative study designs, experiments and process evaluations, and estimation and explanation intentions to generate understanding.

3 *Embracing the mess.* Rather than only looking for clarity and successful evaluation outcomes, they propose stepping back to see the diverging, contradictory results accumulated across a range of interventions to gain better understanding of what did and did not happen.

Building a body of evidence in this manner will, they argue, provide a way of balancing the need for internal validity provided through controlled study designs with the external validity of practice-based studies (Ogilvie, Bauman, et al., 2020). Having a broader range of studies to call on will ultimately create not only a bigger evidence base, but also one that that optimises the unique shape and size of each study (Ogilvie, Bauman, et al., 2020).

[7] Ogilvie, Adams et al. (2020), p. 205

6 Features of existing evidence base tools

The evidence collected during the literature review needed to be made available in an evidence base tool that is designed to make it easy for policymakers, practitioners, and other users to locate and understand the existing evidence on the topic.

To facilitate the design of an evidence base tool, a review was conducted of existing tools. Several different types of tools were identified. They can be broadly grouped into the following categories:

- Digital repositories, which provide a web or app-based interface for displaying and organising information. Evidence can be grouped in multiple ways, e.g., by topic or theme. Search tools can be included to allow users to narrow down on the evidence that matters to them. Maps may also be included to display the data spatially (e.g., to show the location of the studies). A good example of this is KonSULT, which was developed by the University of Leeds, and is described as a 'knowledgebase on sustainable urban land use and transport'. However, although the tool is still available online, it is no longer being updated due to the maintenance required to sustain it.
- Interactive assessment tools, which use a database of evidence to create an interactive process where the user can evaluate project ideas. This is done using a series of inputs provided by the user, which are then used to generate suitable content based on the evidence. These tools can be like digital repositories, but their focus is on providing an assessment (rather than allowing the user to explore the evidence). The KonSULT tool could be considered a hybrid of the two, as it provides both a knowledge base and the ability to assess policy measures through the 'Measure Option Generator' feature. Two examples of tools more focused on the assessment process are Harvard's Co-benefits of the Built Environment tool and the UK Government's My 2050 tool.
- 'Playbooks', which are essentially static documents (typically PDFs) which provide summaries of the evidence. The summaries are kept concise to get key points across quickly and graphical elements can also be included to provide reinforcement of the information. An example is The Workshop's 'How to Talk About Mobility and Transport Shift' guide.
- Infographics are like playbooks, but more focused on the visual aspect of displaying the information, and therefore generally include less content (with their main purpose being to convey the most essential information graphically). An example is Healthcare Without Harm's series of infographics on health.
- Multimedia content, e.g., explainer videos, which can be used to provide evidence summaries. Sometimes this content is included in an interactive course format to help people learn about the evidence in a more hands-on way. An example is the United Nation's series of videos on sustainability.

Each of these types of evidence base tools have pros and cons. Playbooks and infographics are widely used and are relatively straightforward to implement, but they cannot easily be updated with new evidence, and they do not provide the user with ways to search and filter content. Multimedia content and interactive courses can be very engaging, but they require significantly more work to create, and are less suited for those who just want to quickly locate key information. Interactive assessment tools and digital repositories provide a good balance of interactivity and flexibility, but they require careful design to ensure they do not overwhelm the user with too much information. They also require resources to maintain if they are to be useful.

The findings from this review were included in the second workshop, where the various features of the evidence base tools were discussed.

7 Sense-making workshop

The second workshop in November 2022 brought the research partners back together to review and make sense of the outcomes of the literature and practice reviews, and to give guidance on the design of the evidence base output. The workshop was again hosted on Teams and the Miro whiteboard platforms and attended by representatives from Christchurch City Council, Te Kaunihera o Te Tairāwhiti Gisborne District Council, Rau Tipu Rau Ora (RTRO) (Tairawhiti regional leaders' group), and Waka Kotahi.

A summary of findings from the review stages was presented and concluded with the following takeaways:

- Lots of relationships are proposed in the literature but evidence testing of relationships is limited.
- Available evidence shows many co-benefits associated with reducing GHG emissions through urban form.
- Combining evidence should be combined with other ways of knowing, e.g., indigenous knowledge.
- How accurate does evidence have to be to make a decision? 'Accurate enough to act'.

Two consensus-building exercises were run to identify the qualities and features needed for a useful evidence base platform:

Qualities

Participants identified four important qualities they desired of evidence, summarised in Figure 10 below. When asked to agree on the most important, the consensus was that they interact with each other and therefore no one quality was more important than the other.

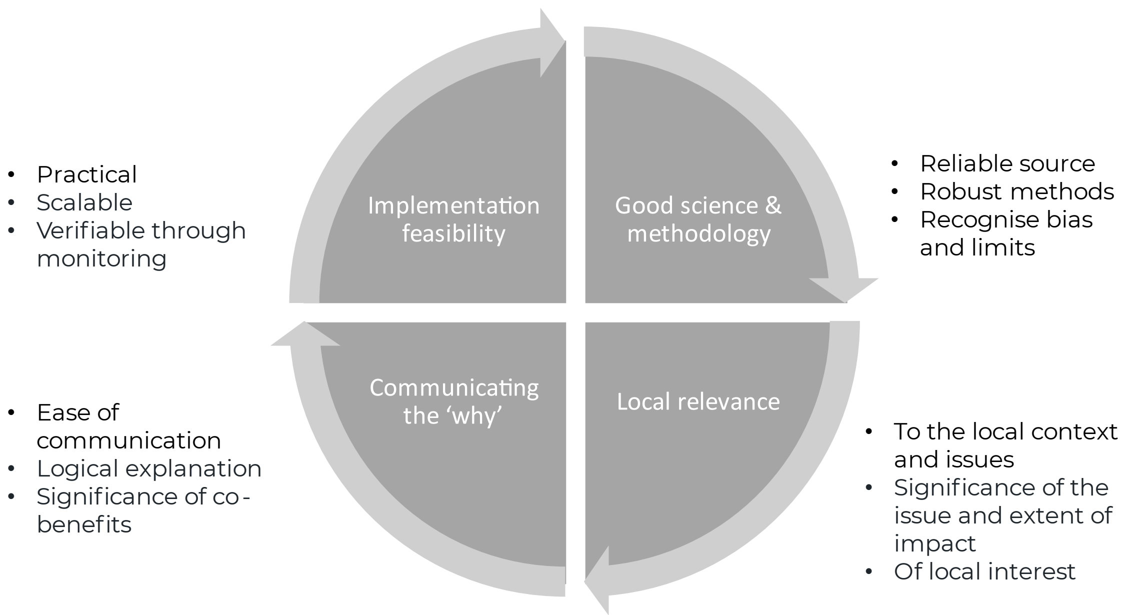

Figure 10: Qualities of useful evidence

Features

The features of existing evidence base tool were presented to the workshop (Figure 11).

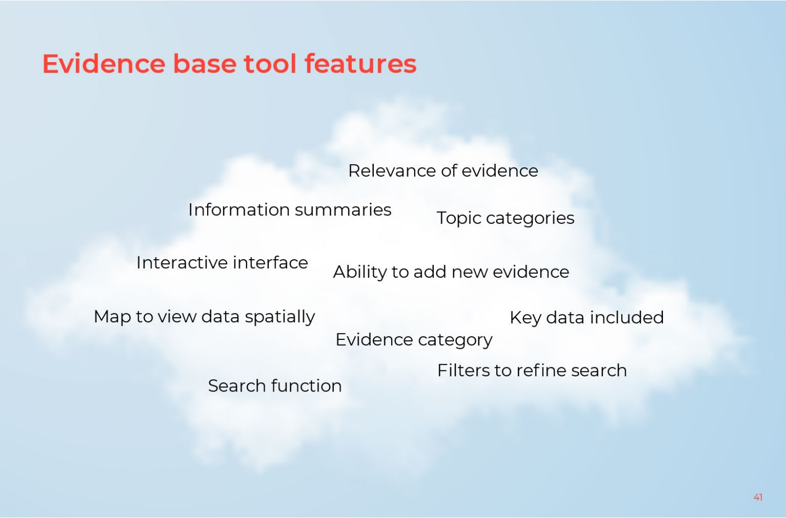

Figure 11: Features of existing evidence base tools

Participants were then asked to consider which features were important for useability, and how they related to the four evidence qualities. The features were mapped on to the qualities with additional features added where appropriate. The discussion revealed how features could be relevant to several qualities, and some functionalities (e.g., having a search function) were related to all four qualities.

The concluding map showed how good quality evidence can be made useful through the design features of a platform. For example, having information summaries could help communicate the 'why' of an intervention.

Figure 12: Mapping evidence base tool features to qualities

Three themes emerged from the discussion to guide the tool design.

1. Recognising the diversity of information and communication needs. Participants talked about a wide range of potential users of information. They included a desire for infographics to simply convey study findings to community members, to being able to learn about the research data and methodology of an intervention.
2. Providing convenience and complexity in one space. The interactive searchability features were seen as a means of making the tool easy to use as well as allowing information about complex matters to be held and accessed through the tool.
3. Connecting different sources of knowledge. Participants saw a useful tool as one that draws connections across the intervention evidence base — e.g., describing interventions by their scale (e.g., neighbourhood or network) and location. They also talked about the opportunity to connect the intervention evidence and other forms of knowledge (e.g., other related evidence and modelling).

The workshop concluded with two observations of what a 'good' evidence base tool should look like:

1. Where should it be held?

   Where it was publicly available and backing to provide 'weight' and support.

2. Who should be involved?

   With motivated people contributing from across sectors so it meets their evidence needs.

8 Evidence base prototype

We designed an evidence base tool based on the lessons taken from the second workshop. The tool is a spatial database that maps studies based on where they occurred, with an overlay showing the general climate zone in each area an example of which can be seen in Figure 13.

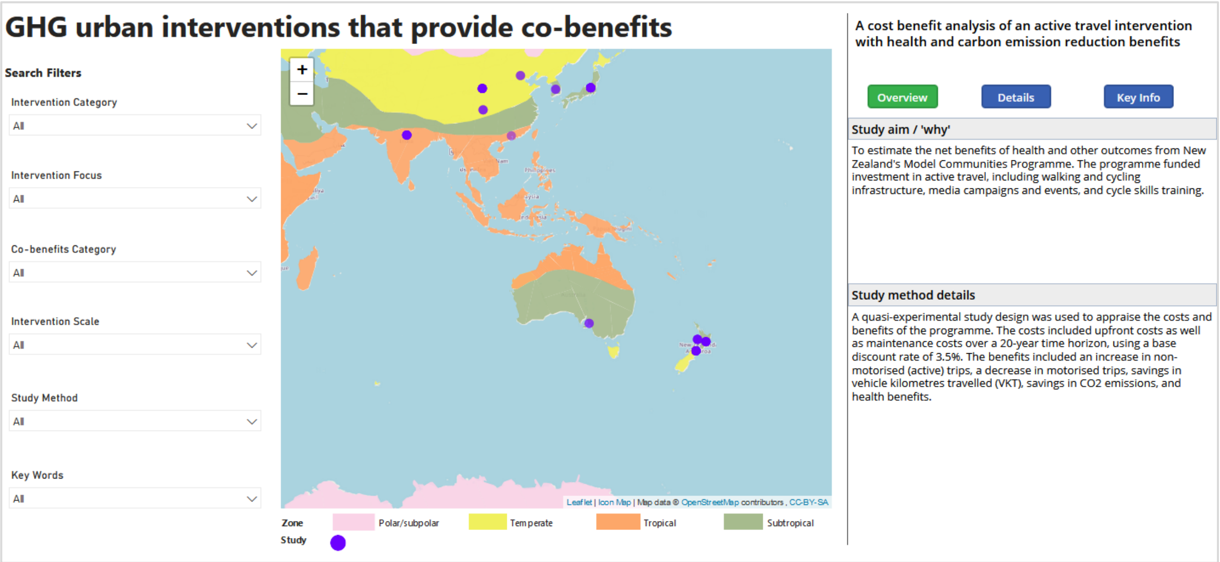

Figure 13: Intervention BI dashboard

To access the dashboard please access the following link:

GHG Literature Review - Power BI

This dashboard allows users to easily identify studies from different countries and different climate conditions. It also provides a range of searchable features to allow users to find studies they are interested in by filtering on the following fields:

- Type of study (e.g., case study, modelling study).
- Type of intervention (e.g., neighbourhood design, land use change).
- Scale (e.g., neighbourhood, city).
- Categories (e.g., urban form, mobility).
- Co-benefits categories (e.g., health, liveability).
- Key words relating to the study.

The filters change the content on the map to show only the relevant studies. The user can then hover over the map points to get a preview of the study's content (e.g., study name, authors, and publication), and click to get more information, including the study aim, method, findings regarding emissions and co-benefits, and transferability of the findings.

The tool's features were based on the key qualities of an evidence base tool identified in the workshop. This included ensuring the tool allowed the user to access relevant information quickly. This is achieved through the use of filters, the quick information panel that appears when hovering over studies, and the information pane which provides more detail grouped into sections, creating several 'layers' of information.

Microsoft's Power BI data visualisation software was used to create the tool. Details of the studies were stored in a spreadsheet, which includes all the relevant filter and information fields, as well as coordinates for the study locations. Power BI was connected to this data to populate the tool with the studies.

The tool should be considered as a prototype proof-of-concept to demonstrate functionality. Future iterations could expand and refine the feature set to improve its usability. This would be particularly important if it was to be populated with more studies, as this may require more advanced filtering capabilities (such as the ability to search by typing in key words).

9 Discussion

The literature and practice reviews reported here have identified evidence showing that changes to urban environments at neighbourhood-to-city scales can deliver both GHG emissions reduction and co-benefits for communities. The evidence base has been populated with a total of 20 studies of interventions or urban change. It covered six domains suggested in the wider literature – greening of urban environments, changes to urban form, mobility and transportation, energy, water, and building construction and technology. While the wider literature on emissions reduction suggested multiple aspects of urban form was related to emissions and/or co-benefits, we found the most of evidential support for GHG emissions reduction at neighbourhood-to-city scales was through low carbon transportation and building construction and technology. We found fewer examples of published evidence of interventions or change for emissions reduction through energy, greening urban environments, water, and urban design. Despite our efforts, we were disappointed we were not able to find examples of evidence incorporating Mātauranga Māori or knowledge from other indigenous knowledge that addresses both emission reduction and benefits. It is not clear whether this is because there are few relevant interventions that incorporate Mātauranga Māori and Te Ao Māori or because they are not reported in the literature.

Published studies were not the only source of knowledge, however. We also identified three lessons for how practitioners can manage where there is a paucity of readily available, published evidence that is locally relevant.

1. Knowledge can be increased by fostering connections to other cases, disciplines, perspectives, and experiences. In this way, knowledge can be accumulated and translated to novel settings and problems.
2. Recognising and valuing the different ways of knowing allows local and/or Mātauranga Māori to be incorporated, as well as technical expertise from outside the project team.
3. Where there is limited data and knowledge, it can be generated in novel ways. Monitoring, accumulating, and reporting data over different projects was seen as critical to ensuring necessary actions can be taken.

The knowledge gleaned from both literature and practice reviews showed there were multiple ways forward for reducing emissions and delivering co-benefits at neighbourhood-to-city scales. They included small scale changes generated at local community levels e.g., community gardens (Bochner et al., 2018) and the Tūrangawaewae Marae carpark sealing practice case. Network-level approaches were also identified e.g., reducing the embodied carbon of stormwater infrastructure (the Copenhagen practice case), changing to decentralised infrastructure (Chang et al., 2017), or enabling more emissions efficient recycling (Sokolow et al., 2016). Other approaches were more holistic and complex, addressing urban form and behaviour change (Chapman et al., 2018; Hachem, 2016) and decision-making around transport and land-use investment (e.g., the mode shift practice case).

Intervention opportunities

Based in the evidence reviewed here, we have identified three significant pathways for reducing emissions and delivering community benefits through changes to urban form in Aotearoa New Zealand: greening urban environments, infrastructure networks, and compact urban form. They can provide the best opportunities for significant change primarily because they provide multiple avenues for emission reduction while accruing multiple benefits to communities.

Greening our neighbourhoods, towns, and cities encompasses a wide range of interventions. They include the use of planting on buildings, such as green roofs and walls; groundcover and trees on streets; using open space for food production; and using open space and planting for stormwater management. They can contribute to emission reduction through carbon sequestration, energy savings by reducing cooling and warming requirements, and reducing the need for carbon-intensive infrastructure such as stormwater pipes. Greening interventions contribute to the functioning of neighbourhoods, towns, and cities through improved physical, mental, and social health outcomes, more affordable services, and improved quality of life.

A key feature of greening initiatives is that there are opportunities at multiple scales and through multiple avenues. Individuals can increase planting in and around their private properties and specify green infrastructure as part of building requirements. Private and public urban developments – both green- and brownfield - can incorporate greening through landscape design. A strategic city-wide approach to the management of public greenspace could plan for equitable access to good quality open spaces, improve the quality of walking infrastructure, improve water quality, and reduce flood risks.

The greening of urban environments is a significant pathway to emissions reduction because the benefits of greening can accrue to both the individual or organisation initiating them, and to the wider community. Greening can reflect Mātauranga Māori through the appropriate selection and use of planting and be part of integrating Te Ao Māori perspectives into places. Pedestrians benefit from the localised cooling effects and improved air quality of street trees. Swopping concrete surfaces for planting can reduce the impacts of rainfall run-off on downstream neighbours and the natural environment. Walking (rather than driving) along pleasant streetscapes to neighbourhood destinations reduces congestion as well as improving individual and community wellbeing.

Infrastructure networks offer the opportunity to reduce the embodied and operational emissions of assets such as pipes and water treatment plants. The network nature of transport and water infrastructure means that decisions made at organisational levels can influence community-wide emission-reducing behaviours and outcomes. For example, improving active and public transport options across a network can reduce GHG-emitting light vehicle travel and improve access to community resources, education, and employment. Resource (and cost) efficiencies in water infrastructure can be improved through low carbon designs of and use of materials, increasing the affordability of services for communities and households.

Networks also offer the opportunity for communities to influence how services and amenities can be effectively and efficiently delivered through infrastructure. For example, community desires for better water quality can lead to infrastructure changes such as daylighting streams and recycling of wastewater.

Increasing the compactness of urban form is a pathway for integrating many of the interventions identified in the evidence base. By reducing the distance to get to everyday destinations, non-car, lower carbon transport modes become more viable options. Denser buildings offer energy efficiencies. The land use mix in compact urban form can be used to prioritise space for services and amenities, increasing the accessibility to communities and improving liveability. It also provides the opportunity to use the public space to reduce emissions, for example, through using low carbon materials.

How compact urban form is achieved is critical to delivering both emissions and community benefits – the urban form needs to be liveable as well as compact. Tools such as LCA's can help decision-makers explore the implications of design options and establish standards and requirements for buildings and infrastructure. HIA's can identify where wellbeing and equity gains can be made. Overarching frameworks can establish the desired outcomes of investing in urban form – what matters most to the communities it serves.

Opportunities for strengthening the evidence base

This project was a response to a need for better access by decision-makers to knowledge and transparency in decisions about emissions reduction, urban form, and co-benefits. They want to know — 'If we do 'X', will it mean 'Y' and 'Z' happens?' The development of the review and subsequent evidence base was guided by engagement with users of evidence. Together we established that evidence needed to cover a wide range of co-benefits and types of interventions, be robust and trustworthy, and represent a range of values and priorities, including indigenous knowledge and perspectives. Overall, we were able to find evidence of the conceptual pathways identified as important to them. We found evidence that well-functioning neighbourhoods, towns, and cities deliver multiple outcomes through mixed use forms, with access to wellbeing resources.

There were limitations in what was covered, however. Given the widely observed challenges generating evidence of interventions addressing complex issues, it was not surprising that we found a considerable 'epistemological gap' (Albris et al., 2020) between what was needed by decision-makers and what was available in the literature. There were relatively few cultures represented across the studies, and we were unable to find studies meeting our criteria that specifically represented indigenous perspectives and values. The Tūrangawaewae practice review highlighted the value of incorporating local and technical knowledge to protect and enhance the mauri (life force) of the Waikato Awa.

The findings from the reviews show that not all the knowledge required to act is available from established evidence sources, and in some areas, there appears to be very little evidence based on interventions and/or modelled change. While there is discussion in the literature about the potential for smart technology to reduce emissions and deliver co-benefits through changes at urban scales (e.g. Al-Thani et al., 2018; Etedadi Aliabadi et al., 2021), actual interventions or modelling do not appear to have been widely evaluated for co-benefit outcomes.

Some of the aspirations for evidence have changed from the original intent. The studies have not been analysed for their research quality, which potentially limits confidence in the findings. Following the 'mosaic' approach recommended by Ogilvie, Bauman et al. (2020) we wanted to incorporate a diverse range of methods in the evidence base without prioritising one approach over others, particularly given the small number of studies. Accordingly, the evidence base has categorised studies by the evidence type so that users can choose to review evidence by method.

Variability in the aims, methods, and reporting across the studies made assessment of the implementation feasibility and/or the local relevance of studies unhelpful. While it would have been desirable to be able to compare the outcomes and impacts of studies by scale, sociodemographic factors, and timeliness (as discussed in the workshops), the relevant information was often missing. Given the wide range of topics and intervention purposes represented in the evidence base, this is unsurprising. The studies were also widely spread across countries and settings. To help users, the evidence base has provided information on contextual factors by mapping studies to visualise their global context and categorising them by scale. A qualitative assessment of transferability to Aotearoa New Zealand urban settings was also provided, with comments added where there may be additional qualifying factors (e.g. where mode shift investments can be made).

Given the variability of what is reported and the observed 'epistemological gap', it is worth considering how the process of evidence generation affects what is ultimately available to decision-makers. By and large, what counts as evidence, particularly high-quality evidence reported in academic journals, is more about reporting whether an intervention has worked, rather than providing decision-makers with information about whether an intervention is appropriate.

Evidence generation requires four qualities:

- The intervention needs to be *observable*: for an intervention to be evaluated data needs to available before, during and after an intervention. For example, failure to gather data on behaviour patterns or resource consumption before a change in infrastructure will make it difficult to assess an intervention's impact. Changes need to be monitored for sufficient time and geographical scales to allow for behaviours to evolve and consolidate.

- Evaluation needs to be *fundable*: Generating evidence of interventions requires funding to support evaluation and reporting, either as part of the evaluation of an investment or as part of academic research. Challenges come from the academic model which is generally dependent on securing funding from highly competitive grants. Smaller scale evaluations may be fundable as part of student-led research, which will favour the reporting of relatively simple, short-run interventions. Non-academic evaluations of interventions (e.g., infrastructure or policy changes) also require dedicated funding available before and after the intervention. Where behaviours might take time to 'bed in' in response to change, evaluation funding may need to be de-coupled from the final completion of (for example) a cycleway project. Multi-factorial interventions may require ongoing evaluations as programmes evolve and interact (Stappers et al., 2020). The challenge is in ensuring the evaluations' design will be appropriate to the intervention as well as providing a suitable level of robustness.
- Evaluations need to *publishable*: Routine intervention evaluation reports are published in the 'grey literature' but are often less subject to quality controls in terms of methodology, what is included in the evaluation, and reporting protocols. They may also be less searchable. Reporting in peer reviewed academic literature is restricted by a competitive publishing requirement. For a paper to be published in high impact journals, it generally needs to be novel and 'moving the field forward' in some way. Within the academic world, there is a known publication bias against negative or null findings, meaning it is harder to contribute to the evidence base about what does not work. One approach authors use to work around this is to focus on one part of an intervention that was successful, with less attention given aspects with little or no change.
  The publication process can also filter out information that is needed by decision-makers. Typically, academic papers are particularly constrained by word counts which limit the amount of information presented. A decision-maker will want contextual information to evaluate the likely effectiveness and transferability of an intervention to another setting — will it work here? Will an energy or water intervention targeted at suburban family households have a similar impact on different household circumstances? In an inner-city household? Contextual information is also critical to being able to attribute the impact to the intervention. It requires contextual information to determine how much difference an intervention made compared with other concurrent factors.
- Interventions need to be *reportable*: The type of intervention can affect how easy it is to report on. Strategic-level, longer term, more comprehensive interventions, or changes will require more resources (i.e., funding), take longer to both implement and see change, and may come to fewer definitive conclusions than a randomised control trial (for example) that targets individuals. Longer term, more complex projects are riskier and therefore typically less likely to be funded and implemented, and then able to be evaluated (Ogilvie, Adams, et al., 2020). Projects that engage closely with communities are also 'messy' and the intervention becomes part of the context over time and therefore harder to distinguish from the outcome (Stappers et al., 2020); yet they may be ultimately more effective at achieving mode shift in populations.

Due to the above qualities, there are likely to be many more interventions undertaken than evaluated, and many more evaluated than accessible published reports. The risk is that a restricted evidence base in turn restricts the types of interventions funded if decision-makers rely on reported evidence alone.

While the current evidence base of published interventions is relatively small, there are opportunities to expand knowledge. New methods — e.g., those used by Chapman et al. (2018) — will allow high quality, comprehensive evaluations of complex interventions that address urban form and co-benefits, e.g., Te Ara Mua – Future Streets and London's 'Mini-Holland' (Aldred et al., 2019; Aldred & Goodman, 2020) which will add considerable value to the evidence base in the future. Other studies evaluated impacts on both emissions and co-benefits from changes to buildings (e.g., Preval et al., 2010), but were not at neighbourhood-scale per se. The emissions and health impacts observed by (Preval et al., 2010) of the Housing, Heating and Health study He Kainga Oranga could be scaled up through urban regeneration investments, delivering community wide benefits of healthier children with fewer school absences. Research is currently underway in Aotearoa New Zealand, exploring these pathways including Public Housing and Urban Regeneration and Te Hotonga Hapori – Connecting Communities.

The practice reviews we undertook all faced challenges of insufficient or unclear information where the reported evidence was limited. A clear conclusion from them was that through connections and learning from others, expertise and experience can add to the available evidence and help fill gaps. Questions remain around how experience and expertise can be used in combination with evidence from the literature in ways that ensure robust and transparent decisions. How can expertise and experience combine with evidence to generate complementary knowledge? To interpret and translate evidence into local contexts? And local values? Are there situations where one type of knowledge is preferred over the other?

10 Conclusions

There is international and domestic evidence that neighbourhood-to-city scale interventions or changes to reduce GHG emissions can also deliver co-benefits and contribute to well-functioning neighbourhoods, towns, and cities. This research found the content and type of available evidence for interventions was highly varied. The final evidence base covered six intervention domains (i.e., greening of urban environments, changes to urban form, mobility and transportation, energy, water, and building construction and technology) and included multiple evaluation methods, scales, and benefits.

Many of the emission reduction interventions in the evidence base covered multiple domains and provided multiple benefits. The results suggest that while mobility and transportation were most frequently reported, the pathway to emissions reduction was often through compact, more liveable urban form and reduced energy consumption. Water and energy were also interdependent. Greening of urban form provided multiple ways of reducing emissions and delivering co-benefits — urban gardens provide local food, reducing the need to travel and green roofs cool environments.

While many pathways to emissions reduction and co-benefits through urban form are suggested in the literature, overall, we found a relatively small number of studies that evaluated and reported on the extent of emissions reduction, associated benefits, and the actual changes to urban form. This is likely to be a feature of the complex nature of these interventions and the relatively new methods for assessing GHG emissions.

Making meaningful comparisons and quality assessments across studies was limited by the small number of studies and their highly variable nature. To meet the needs of users as practically as possible, the evidence base has applied lessons from user workshops in the design of the tool. The spatial nature of the tool allows for additional contextual information to be added. Searchable filters and categories have provided entry-level details that are supported by access to more detailed information as required.

In the absence of complete information, the insights gained from practical examples of urban interventions have highlighted the value of expertise and experience alongside evidence. This project has demonstrated the challenges faced when trying to base emissions reduction decisions on evidence, but also the possibilities for combining different forms of knowledge to make good decisions. In the words of one practitioner: 'how accurate do we need evidence to be? Accurate enough to act'. In the absence of a comprehensive, high quality evidence base, further work is needed to better understand the barriers and enablers to using evidence so decision-makers can understand, interrogate, and gather evidence in practical ways.

Intervening at neighbourhood, town, and city scales to reduce emissions cannot be achieved by a single type of intervention. From the evidence, we identified three priority pathways that provide the best opportunities for individuals, communities, and local and national agencies to play their part (greening, infrastructure networks, and compact urban form). Greening urban environments can be achieved through small-scale community-led interventions as well as broader-scale national and local authority initiatives. Changes to a low carbon design and operation of infrastructure networks can have far-reaching consequences for reducing embodied and operational emissions, and support wide-scale, emission-reducing behaviour change. And finally, increasing the compactness of urban form offers multiple avenues to reduce emissions through behaviour change, material use, and resource efficiency, and when done well, ultimately improve the quality and functioning of Aotearoa New Zealand's neighbourhoods, towns, and cities.

Recommendations for intervening in Aotearoa New Zealand's urban form

A portfolio of interventions will be required to deliver emissions reduction in ways that also lead to well-functioning neighbourhoods, towns, and cities. The following recommendations for communities and agencies build on the lessons learned from the evidence base.

- Provide decision-makers with the ability to understand, interrogate, and gather additional evidence so they can answer the question - 'how could it work here?'
- Match the type of intervention with who can successfully implement it. For example, individual people and sites can contribute significantly to low carbon urban form through greening of buildings and sites, but less so through changes to wastewater treatment infrastructure.
- Invest in a balanced portfolio of short-term, small-scale projects (such as greening of streets) with longer-term, complex programs (such as urban regeneration).
- Take a multi-scale approach to planning interventions so that changes at building, neighbourhood, network, and city scales can be enhanced by synergies between them. For example, optimising the extent and type of tree cover around buildings and along individual streets will be important for creating liveable and sustainable compact urban forms, and may be easier to achieve if planned for in advance.
- Consider how community values, needs, and knowledge, including Mātauranga Māori, can be reflected in emission reduction interventions, for example, the desire to support local food production and/or sharing knowledge.
- Consider how interventions can be staged to best achieve both emissions and community outcomes. For example, which communities will benefit the most from improvements to low carbon transport infrastructure?
- Take a long-term view so that interventions can be adapted as they evolve, and new opportunities can be seized as they arise.

Recommendations for strengthening the evidence base for urban form interventions

Taking lessons from the literature and practice review exercise, and the commentary on generating and using evidence in similar challenges, the following recommendations for developing an evidence base are:

- Support a 'mosaic' approach to evidence that reflects the diversity of interventions, methods for evaluating and reporting, and information needs of information users. Develop ways of better combining and synthesising knowledge across evidence and intervention types to build a more wholistic view of interventions.
- Support the evaluation and reporting of interventions that reflect Te Ao Māori worldviews and incorporate Mātauranga Māori, including studies done by Māori with Kaupapa Māori research principles.
- Support the accumulation and sharing of knowledge with information users to better address uncertainties about what 'works', especially regarding novel and/or complex and wholistic interventions.
- Acknowledge that not all the knowledge required to inform decisions about emissions reduction through urban form can be sourced from formal, reported evidence.
- Develop ways to facilitate the integration of experience and expertise alongside formal evidence in ways that provide robustness and transparency.
- Support evaluation methods that enhance comparability across studies and evaluations, including geographical, environmental, economic, socio-cultural, and built environment features.
- Develop methods to aid the interpretation and translation by users of evidence to the Aotearoa New Zealand urban and cultural environment.

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