MAIN ARTICLE

Using causal loop diagrams to develop evaluative research propositions: opportunities and challenges in applications to nature-based solutions

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Abstract

Causal loop diagrams (CLDs) are often used to provide an overview of important systemic elements related to an issue, rather than to inform empirical evaluations (studies which assess changes following an intervention using observed data). We suggest that empirical evaluations may benefit from the development of systems-informed research propositions (specific testable causal assumptions with an emphasis on feedback loops) used to guide subsequent data collection, hypothesis testing and interpretation. We describe a qualitative systems-thinking informed approach building on preexisting CLDs, published evidence, and expert/stakeholder consultation and reflect on our experience applying this to the early stages of two nature-based solution (NBS) evaluations. We reflect on our experience and suggest that CLDs can be usefully employed to develop systems-informed research propositions to inform subsequent empirical evaluation. This may lead to novel policy-relevant research propositions which differ substantially from effectiveness-oriented ("did it work?") research questions.

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Introduction

The importance of large-scale policy and infrastructure interventions

Major challenges (e.g. noncommunicable diseases, climate change) necessitate large-scale interventions that operate within and across complex systems (Raymond *et al.*, 2017; Rutter *et al.*, 2017; Seddon *et al.*, 2020; Skivington *et al.*, 2021). These are often policy or infrastructure interventions, such as introducing taxes on health and environment-harming products, regulations

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mandating cycle lanes and street trees in cities, and investing in large-scale restoration of natural areas. These kinds of interventions often require a confluence of factors, including political will, to align and produce a window of opportunity (Kingdon, 1984). As such, these interventions are very much *not* under the control of the researchers who hope to study them. From a research team's perspective, these interventions are "predetermined," i.e. determined outside of the scope of the researcher's influence. Nevertheless, evaluating these interventions is valuable, as real-world evaluation evidence can help adjust how interventions are "course corrected" over time to improve their function (Ogilvie *et al.*, 2019), as well as improving new instances of the intervention elsewhere.

A different use of the word "evaluate"

Many studies have used system dynamics (SD) simulation to "evaluate" policy options by simulating various scenarios, often prior to implementation (Abbaspour and Dabirian, 2019; Ansah *et al.*, 2020; Biroscak *et al.*, 2014; Hovmand *et al.*, 2009; Kang *et al.*, 2018; Urwannachotima *et al.*, 2020). These models assess the underlying structure of an issue and may identify unexpected impacts of a well-intentioned policy or intervention. However, the use of the word "evaluate" in this context differs substantially from the meaning used in policy or infrastructure evaluations, in which "evaluate" means to assess real-world outcomes using observed data, typically with a natural experimental evaluation design. It is this latter sense of the word that we use in this article.

Different types of evaluative research questions

The kinds of predetermined interventions described above can rarely be evaluated using methods such as randomized control trials (RCTs), since researchers cannot, typically, manipulate or control who receives the intervention, violating the basic premise of an RCT. Instead, researchers increasingly use natural experimental evaluation designs to assess the impact of these types of interventions (Craig *et al.*, 2022, 2012; Ogilvie *et al.*, 2019). The de facto research question in a natural experimental evaluation tends to be: "to what extent did the intervention make a difference to the outcome of interest?" Other components of an evaluation may consider process ("was the intervention implemented as intended?") or distribution of impacts ("who did it impact and why?").

These questions map onto the four research perspectives identified in the recently updated Framework for Developing and Evaluating Complex Interventions: efficacy, effectiveness, theory based, and systems perspectives (Skivington *et al.*, 2021). Questions posed from an efficacy perspective (e.g. does it work in a controlled setting?) are typically answered using

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experimental studies (and may be addressed using RCTs). These typically inform the design of future policy or infrastructure interventions. Effectiveness questions tend to be the most common in natural experimental evaluations and include some variant of "did it work when delivered in a real-world setting?" Theory-based questions consider a theory of change and consider mechanisms and the distribution of impacts across subgroups. Finally, systems questions entail considering how the system and intervention adapted to one another. To date, efficacy and effectiveness questions have tended to dominate (Skivington *et al.*, 2021).

Potential to inform evaluative research propositions from a systems perspective

Recent guidance has advised that if an evaluation team aims to adopt a systems perspective, they might consider "how do the system and intervention adapt to one another?" (Skivington *et al.*, 2021, p. 3). While this is thought provoking, it is also quite a broad prompt. Attempts to answer this type of question may encourage evaluation teams to produce descriptive rather than explanatory results. We suggest there is value in developing systems-informed research propositions to bridge the gap between this broad prompt and the practicalities of conducting an empirical evaluation. We describe what we mean by a "systems-informed research proposition" in two stages below.

First, we define research propositions generally as "novel statements specifying relationships between concepts" (Ulaga *et al.*, 2021, p. 396), or in other words, testable assumptions about a potential causal relationship. For example, consider the following research proposition (RP1): the presence of trees reduces mental fatigue and acts of aggression amongst public housing residents. This is a testable causal statement and was empirically assessed by Kuo and Sullivan in their natural experimental evaluation of nearby nature and public housing blocks in Chicago (Kuo and Sullivan, 2001). In this study, the authors considered: "First, does nearby nature reduce aggression and violence? And second, if so, is this effect mediated via attentional restoration?" (Kuo and Sullivan, 2001, p. 548). These questions have been posed from a joint effectiveness ("did it work?") and theory-based (considering mechanisms) perspective.

Second, we define *systems-informed* research propositions as testable assumptions about causal feedback relationships. For example, RP1 could be expanded through a feedback lens (RP2): the presence of trees reduces mental fatigue and acts of aggression amongst public-housing residents, creating a positive feedback loop whereby residents are less likely to vandalize nearby trees and more likely to engage in acts of tree stewardship, resulting in increased growth and improved health of the trees, which continue to reduce residents' mental fatigue and aggression over time. This testable

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statement summarizes a feedback loop and reflects a more granular version of the "how do the system and intervention adapt to one another?" question central to taking a systems perspective (Skivington *et al.*, 2021, p. 3).

There is such a strong tradition of posing effectiveness-oriented research questions in policy and infrastructure evaluations that even when research teams use systems mapping, group model building (GMB), and system dynamics modeling (SDM) methods, it can be challenging to pose systems-informed research questions. This represents an important potential role for qualitative systems thinking: to contribute to the development of systems-informed research propositions at the start of an empirical evaluation. Reflecting on our own experience, we explore the extent to which systems thinking used in this way could usefully contribute to the empirical evaluation of nature-based solutions (NBS) and consider the conditions for broader applications.

Nature-based solutions and impacts of health and well-being

In our efforts to design evaluations from a systems perspective, we focused on one group of large-scale interventions, nature-based solutions. NBS are defined as "solutions to societal challenges that are inspired and supported by nature" and include, for example, efforts to introduce street trees in urban spaces and restore wetlands in rural areas (Raymond *et al.*, 2017, p. 15). A key feature of NBS is that they produce multiple benefits across environmental, social, and economic domains (Jones *et al.*, 2022; Raymond *et al.*, 2017). In recent years, NBS have been prioritized as recognition of their potential benefits (and the magnitude of related challenges) increases.

NBS are also challenging to evaluate, for many of the reasons described above (e.g. a limited ability to control intervention roll out, possible unintended consequences, etc.). There have been calls to adopt a systems-thinking perspective concerning the design, development, and evaluation of NBS, and some recent examples (Castro, 2021; Coletta *et al.*, 2021; Menconi *et al.*, 2021). For example, Coletta *et al.* (2021) used CLDs to consider the potential benefits and trade-offs of proposed NBS interventions, to inform intervention selection. However, we are not aware of any attempts to use a systems lens to inform the evaluation of an NBS.

Aim of this article

We propose an approach to develop systems-informed research propositions to evaluate large-scale policy or infrastructure interventions and reflect on our experiences of doing so around two NBS interventions.

Broadly, we propose the following process drawing on guidance around GMB, CLDs, and applied systems-informed evaluation frameworks (Luna Pinzon *et al.*, 2022; McGill *et al.*, 2020; Sterman, 2000; Vennix, 1999):

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1. Represent the underlying system
2. Develop an understanding of the intervention
3. Identify links between the intervention (and its influences/impacts) and the underlying system
4. Generate systems-informed research propositions from the CLD, drawing on systems archetypes where relevant
5. Sense-check the systems-informed research propositions with subject area experts and stakeholders

This process is intended to inform the design of a subsequent empirical evaluation. To illustrate what this process may look like in practice, we briefly describe our experiences in developing systems-informed research propositions concerning two NBS: street trees in urban environments and the restoration of a wetland in a rural community. We reflect on the opportunities and challenges afforded by taking this approach.

Proposed process

We describe the rationale, process, and value added of each step in more detail before proceeding to two applied examples.

Step 1: represent the underlying system

This first step in our proposed process consists of identifying or developing an understanding of the underlying system within which the intervention will be introduced. For those coming from an SD background, the necessity of conceptualizing the underlying system may seem obvious. However, for those coming from an evaluation background, it is common to start with the intervention and theorize about the proximate and distal impacts of that intervention without explicitly considering the underlying system (Hawe *et al*., 2009b; McGill *et al*., 2020). Identifying the underlying system first represents a substantial shift. The main advantage of this compared to an evaluation approach based around linear conceptual frameworks of environment and health linkages (e.g. using the Drivers, Pressures, State, Impact and Response (DPSIR) model) is that it embraces the potential for feedback loops and may forefront unintended negative consequences.

There are multiple ways to do this. For some topics, an evidence synthesis may already have been conducted and used to develop a summary CLD (Sawyer *et al*., 2021; Wittenborn *et al*., 2016). While this is a departure from participatory approaches to developing CLDs, building on an evidence synthesis-based CLD offers several advantages, including a lower time and resource cost at this stage, and the possibility of including factors which may not be apparent to specific groups of stakeholders. This approach has the

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disadvantages of not representing multiple perspectives or local factors, being limited by the published evidence base and not promoting engagement with systems thinking amongst a wide group of stakeholders and project partners.

Another approach, either when a preexisting CLD is not available or the advantages of using one are not seen to outweigh the disadvantages, is to develop a de novo CLD. This can be done by drawing on the literature, through a group model-building process, or through a combined approach (Kim and Andersen, 2012; Luna-reyes *et al.*, 2006; Rouwette *et al.*, 2002; Vennix, 1999). Developing a CLD solely from literature may share some of the advantages/disadvantages of using a preexisting CLD described above, although it may allow the research team more control and specificity over local contextual factors, while requiring more time to develop compared to a preexisting CLD. A participatory group model-building process is more likely to produce a context-specific rich representation, reflecting the views and experiences of the participants, and can help to expose stakeholders and project partners to systems-thinking concepts early on (Hovmand, 2014). However, this approach is time consuming and resource intensive. Given that this is the first step in developing systems-informed research propositions, which in itself is the first step in an overall empirical evaluation, the evaluation team will need to weigh the trade-offs between various approaches, considering the time and resources required at this stage and subsequent ones.

Step 2: develop an understanding of the intervention

The second step entails developing an understanding of the intervention, which may be done in several ways, for example through (1) the use of a systematic literature review, (2) the review of project documents, (3) consultation with local stakeholders and experts, or various combinations thereof. In this stage, the evaluation team explicitly theorizes about the proximal and distal impacts of the intervention, which should include multiple potential pathways of impact and potential unintended effects. Evaluation teams should also consider proximal and distal factors which influence the introduction of the intervention itself or some aspect of the intervention design.

Step 3: identify links between the intervention (and its influences/impacts) and the underlying system

The third step entails an iterative process of linking the intervention and the underlying system, exploring where there may be interconnections and potential feedback loops. It may be necessary to relabel or reorganize some variables to connect intervention-related concepts with concepts highlighted in the underlying system CLD. Additional intermediary variables may be

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introduced to bridge concepts or make links explicit. This step encourages the consideration of unexpected connections.

Step 4: generate systems-informed research propositions from the CLD

The fourth step entails analysis of the joined-up CLD to develop refutable systems-informed research propositions. We found that it was useful at this stage to generate higher-level, abstracted CLDs, i.e. CLDs that comprise three or four interlinked feedback loops (rather than 10 or 20). This process of moving from a high level of detail to more abstracted level requires a closeness to the material and iterations between high-level themes and detailed cause-effect relationships, akin in some ways to the process of reflexive thematic analysis (Braun and Clarke, 2016). Evaluation teams may benefit from using systems archetypes where relevant (Kim, 1994; Wolstenholme, 2003, 2004). The process of abstracting allowed us to refocus on feedback loops in a way which was not as apparent in the more detailed CLDs. If research teams have the capacity, time, and resources, the development of a system dynamics model would likely strengthen this step. However, producing a full SDM may be beyond the resource capacities of most research teams at the early research proposition stage of an evaluation.

Step 5: sense-check the systems-informed research propositions with stakeholders

The final step entails sense-checking the systems-informed research propositions with stakeholders and making changes to reflect their feedback. Evaluation teams may benefit from focusing on the outputs from Step 4 (the higher-level, abstracted CLDs) and using interactive software (e.g. Kumu) to communicate and elicit feedback on the proposed research propositions.

In the next section, we briefly describe our experience operationalizing this process with two examples.

Applied cases

We briefly summarize our application of this process across two types of NBS: (a) street trees in urban areas in Europe and (b) a large-scale wetland-restoration project in rural Denmark.

We used the process described above to develop systems-informed research propositions, intended for use in subsequent evaluations of these interventions.

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Example A: street trees (the intervention to be evaluated) in urban areas in Europe

Street trees can provide a range of ecosystem services (broadly speaking, benefits to humans from the natural environment) including urban heat mitigation, air-quality regulation, reducing storm water run-off, and aesthetic value (Andersson-Sköld *et al.*, 2015; Salmond *et al.*, 2016). Interest in the climate adaptation potential of street trees is growing, and many local and national campaigns have been launched with the aim of planting large numbers of street trees (Rae *et al.*, 2010; Salmond *et al.*, 2016; Watkins *et al.*, 2017; Werbin *et al.*, 2020). Several recent reviews have considered the impacts of street trees in particular and of urban trees more generally (Mullaney *et al.*, 2015; Salmond *et al.*, 2016; Wolf *et al.*, 2020). These reviews highlight the potential of street trees but also emphasize the challenges in considering the multiple pathways through which street trees are thought to operate, considering unexpected consequences, and evaluating impact.

Our focus on street trees was part of our contribution to a large EU-funded project (REGREEN: Fostering nature-based solutions for smart, green, and healthy urban transitions in Europe and China, https://cordis.europa.eu/project/id/821016) which considered street trees as one type of NBS across multiple Urban Living Labs (ULLs). Street trees were selected based on stakeholder interest across ULLs and perception of feasibility. We were tasked with considering the extent to which street trees and mental health are connected, through a systems lens, and developing related research propositions to guide future empirical work.

Example B: large-scale wetland restoration (the intervention to be evaluated) in a rural/natural area

The frequency and intensity of flooding has increased over the last 70 years resulting in property damage, loss of life, displacement, post-traumatic stress disorder, and a range of other health and well-being impacts (Fernandez *et al.*, 2015). Large-scale NBS projects such as wetland restoration may represent a promising approach to address flood risk in rural and natural areas while also producing additional benefits. In addition to reducing flooding, these kinds of NBS may lead to enhanced biodiversity and increased opportunities for outdoor recreation, as well as other potential cobenefits. However, limited empirical work has been done to assess the purported impacts on human health and well-being (Venkataramanan *et al.*, 2019).

The wetland-restoration project we considered was part of our contribution to a large EU-funded project (RECONECT: Regenarating ECOsystems with nature-based solutions for hydro-meteorological risk rEduCTion, https://cordis.europa.eu/project/id/776866). This wetland-restoration project was underway in Odense, Denmark, and represented a strategic opportunity

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to develop lessons for other possible sites. We were tasked with considering to what extent the wetland-restoration project and mental health/well-being may be connected, through a systems lens, and developing related research propositions to guide future empirical work.

In the subsequent sections, we summarize how we applied our proposed process to both cases.

Step 1: represent the underlying system

In both examples described above, we were tasked with exploring the possible interactions between these NBS interventions and mental health. We drew on an existing evidence synthesis around the systemic drivers, determinants, and impacts of mental health which had been summarized in a CLD (Wittenborn *et al*., 2016). The Wittenborn *et al*. model brought together a wide range of literature around the drivers of mental health through a systems lens, and as such provided a pragmatic starting point for our analysis. We developed a simplified version of their model, collapsing some intermediary biological processes to focus on the social and environmental factors (Figure 1). For example, we simplified Wittenborn's chain linking physical health → physical inactivity → cortisol → monoamines → sleep problem (Wittenborn *et al*., 2016), eliminating the biological processes and additional feedback loops around increased cortisol and decreased monoamines. We represent this instead as physical health → physical activity (transformed in our case from "inactivity") → sleep quality, recognizing the trade-off between completeness and comprehensibility for our purposes.

This provided a foundation for considering possible interconnections between our interventions of interest and the underlying system concerning mental health.

Step 2: develop an understanding of the intervention

We used different approaches to develop an understanding of each of the NBS interventions.

For the street-tree intervention, there was no setting-specific intervention to focus on, so we used existing reviews to identify key empirical studies concerning street trees and both their impacts and factors which lead to the introduction of street trees. We supplemented the initial body of literature on street trees by conducting targeted searches for studies linking impacts of streets trees with factors in Wittenborn *et al*.'s model (e.g. pollen and negative affect). In total, we considered 414 studies and extracted data from 56 key papers. We identified 103 hypothesized causal relationships and extracted data on the cause, outcome, and polarity of each relationship in a standardized Excel template.

For the wetland-restoration intervention, we did have a specific intervention to focus on and used a combination of document review and key stakeholder

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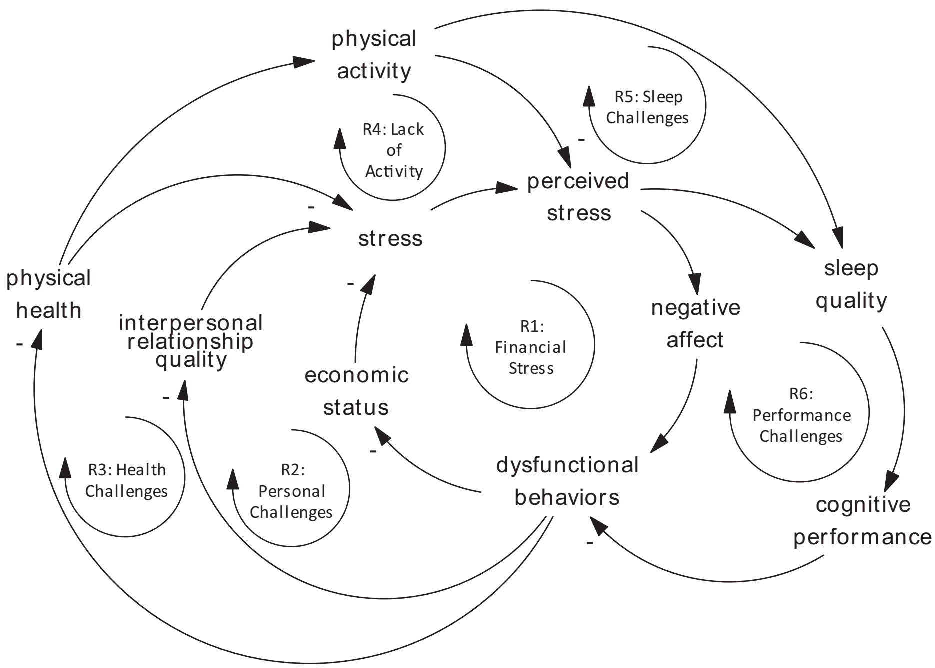

Fig. 1. Simplified causal loop diagrams (CLD) based on Wittenborn *et al.* 2016, with a focus on social and environmental reenforcing loops. Link polarity is (+) unless otherwise shown

interviews to elicit information about how the intervention was intended to operate. We were informed by Deegan's 10-step process for coding causal relationships from text and developing associated causal maps (Deegan, 2009). We extracted hypothesized causal relationships from each project document, including data on the cause, effect, and polarity (±) of key relationships.

Across both projects, we extracted data on the following fields:

- Source
- Cause
- Effect
- Polarity [±]
- Evidence of delayed process [y/n]
- Description

Step 3: identify links between the intervention (and its influences/impacts) and the underlying system

In this step we combined the simplified mental health CLD (Figure 1) with the conceptual understanding of each NBS intervention, separately. In both cases,

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we reorganized variables and introduced additional intermediary variables to make links explicit. Sterman describes the need for this kind of process:

> In many cases, you will need to add additional causal links not mentioned in the interviews or other data sources. While some of these will represent basic physical relationships and be obvious to all, others require justification or explanation. You should draw on all the knowledge you have from your experience with the system to complete the diagram. (2000, p. 158)

At this point, we had developed two quite large and detailed CLDs (see https://kumu.io/ecehh/street-trees-mental-health-overall-causal-loop-diagram-18d0 for the full street-tree CLD and https://ecehh.kumu.io/seden-strand-odense for an interactive presentation for the wetland-restoration project).

Next, we stepped back to analyze the revised CLDs, zooming in and out to consider the CLDs at different levels of detail. We produced simplified CLDs at a higher level of abstraction to summarize key dynamics. We reproduce the street-tree CLDs (Figure 2) and present the wetland-restoration CLD (Figure 3), both of which focused on the ways in which NBS can directly and indirectly contribute to mental health (represented as "negative affect, interpretation, and processing" in the street-tree example and "psychological well-being" in the wetland-restoration example).

In both cases the CLDs illustrate the direct and indirect ways in which the NBS intervention may influence mental health, and how the system around mental health may in turn impact the continued maintenance (or not) of the NBS intervention. For example, in the street-tree case, increased economic status resulting directly and indirectly from street trees (e.g. through increased housing value) may, with a delay, lead to increased municipal tax revenues, increasing the potential resources available for street trees and improving tree health, leading to larger canopies and potentially greater new tree plantings. In the wetland-restoration case, reduced flood risk may also eventually lead to increased economic status, as property values increase when flood-risk assessments decline. This eventual increase in property values may increase the support for both this and additional NBS infrastructure interventions, producing greater support in maintaining the NBS and perhaps expanding it over time. In both cases we illustrate how these feedbacks may influence the intervention itself over time.

Step 4: generate systems-informed research propositions from the CLD

We used the CLDs described above as the basis for developing systems-informed research propositions, which are narrative descriptions of specific loops or combinations of loops. We identified relevant systems archetypes ("success to the successful" and "fixes that fail") which corresponded to patterns we observed in the CLDs and drew on these archetypes in the wording of the research propositions as well.

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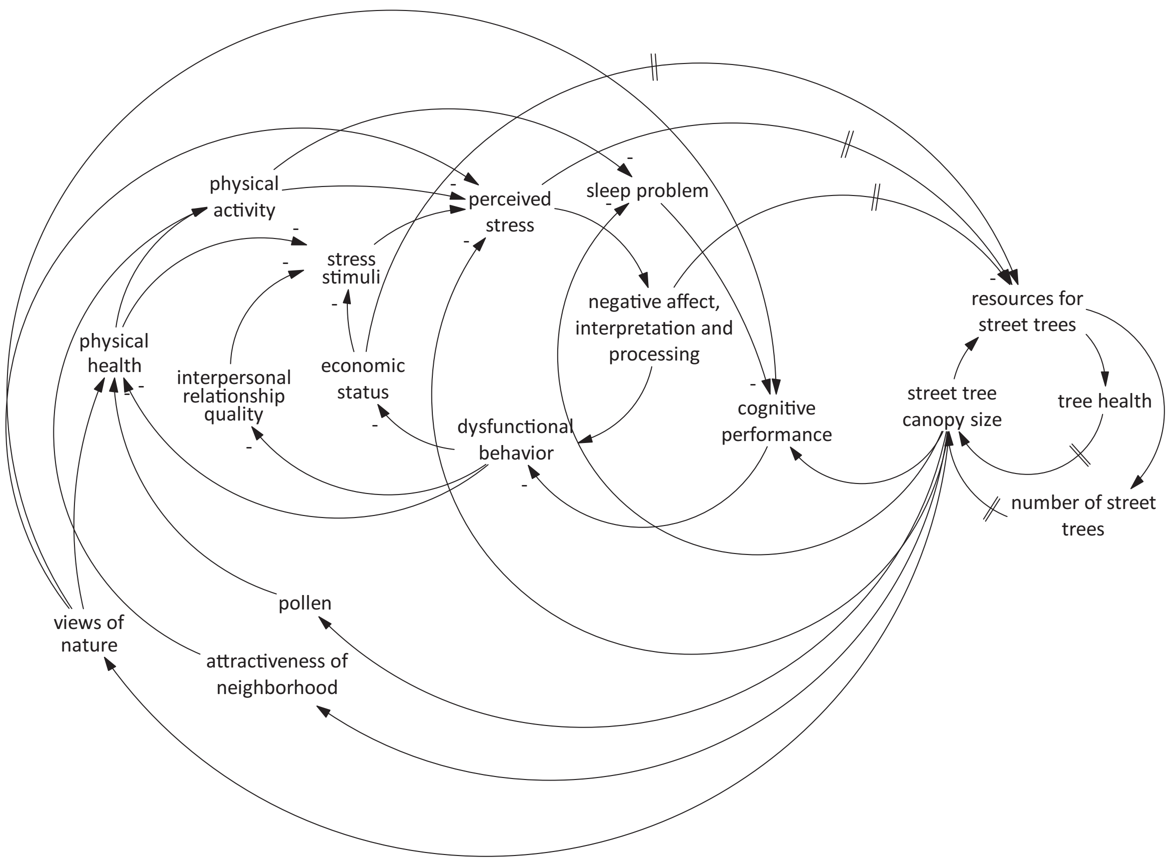

Fig. 2. Street tree and mental health causal loop diagrams (CLD), reproduced from Alvarado *et al.* (2023). Link polarity is (+) unless otherwise shown

For example, in the street-tree work we developed the following street-tree propositions (ST-Ps):

ST-P1: Mental health and street-tree health are linked through reinforcing feedback loops such that increases in resources for street-tree maintenance, over time, lead to increases in mental health, and increased mental health in particular neighbourhoods, over time, leads to increased resources for street trees.

ST-P2: Residents who have experienced the benefits of street trees value them more highly and therefore advocate for additional trees or engage in tree planting to a higher degree than their counterparts with limited experience of street-tree benefits, leading to increasing disparities in street-tree coverage.

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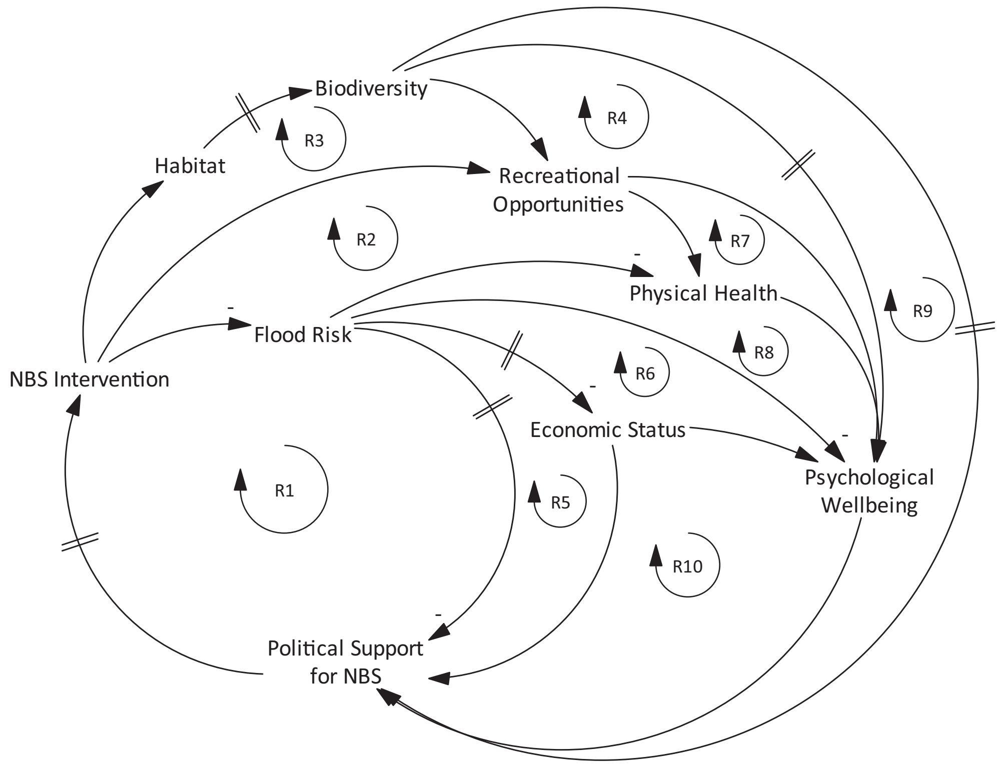

Fig. 3. Intervention-focused causal loop diagrams (CLD) for the wetland-restoration project. Link polarity is (+) unless otherwise shown

> **ST-P3:** Planting new street trees in a disadvantaged neighbourhood may backfire if resources for tree maintenance are not provided, resulting in trees in poor health and an environment of neglect and disrepair, ultimately worsening mental health.

These research propositions can be transformed into setting-specific hypotheses and used to evaluate street trees as an intervention from a systems-informed lens. For example, project partners expressed an interest in assessing whether the policy of encouraging residents to vote on street-tree planting sites had, over time, increased inequalities in street-tree coverage. Did areas with high voter participation already have a high level of street-tree coverage, compared with areas with low voter participation?

In the wetland-restoration project, we developed the following wetland-restoration propositions (WR-Ps):

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WR-P1: Residents may be resistant to the NBS initially, given immediately experienced costs such as perceived loss of agency, a sense that nature takes primary over landowner concerns, and loss of generational connection to land and type of land use.

WR-P2: The intended benefits of the NBS operate over a longer time horizon and may not be experienced or perceived for several years.

WR-P3: However, after a delay, residents may experience benefits around improved opportunities for recreation, higher-quality experiences with nature, and increased home value, with cascading impacts on physical and mental health. These benefits may lead to increased support for NBS in the medium to long term.

Taken together, these research propositions represent an inverted "fixes that fail" archetype, as shown in Figure 4.

This suggests that decision-makers should expect some resistance to NBS and implies that an initial lack of support should not necessarily be a reason to forestall NBS interventions. Instead, shortening the delay with which residents perceive benefits may be a powerful way to increase support for NBS over time and increase future investment and frequency of NBS projects. These research propositions can be transformed into site-specific hypotheses, such as: satisfaction with the wetland-restoration project in Odense was low initially and increased over time, with the biggest increases in satisfaction reported after (1) completion of the recreational infrastructure within the wetland area and (2) averted flooding incidents; additional investments in NBS remained low until after public support was perceived to have increased. These research propositions can also be operationalized for other sites.

Step 5: sense-check the systems-informed research propositions with stakeholders

To sense-check the systems-informed research propositions, we shared them in multiple online workshops with different groups of subject area experts and project partners who provided feedback and additional references for consideration. In each workshop, we presented the CLDs and systems-informed research propositions and described the process we went through to arrive at them. We asked participants whether anything important was missing from the CLDs, whether the relationships and structures represented their understanding of the intervention and system, and whether the identified propositions seemed plausible and relevant. We developed online presentations to allow users to click through the CLDs in a guided fashion, to make the detailed versions more digestible (e.g. https://ecehh.kumu.io/

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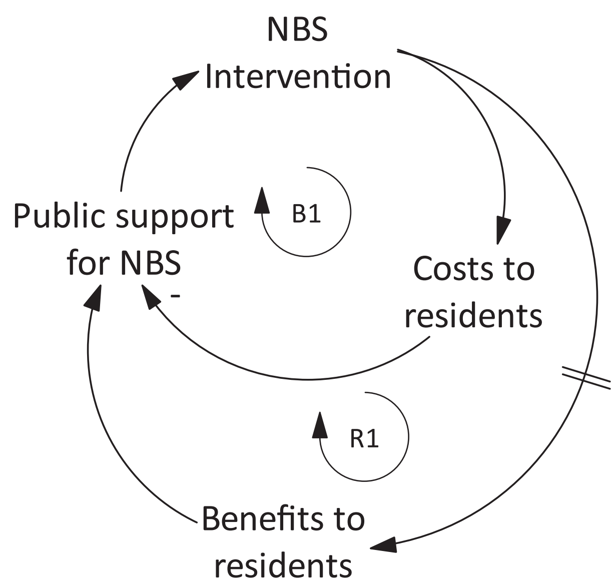

Fig. 4. Simplified causal loop diagrams (CLD) example. Link polarity is (+) unless otherwise shown

street-trees-in-european-ulls). We incorporated feedback and updated the CLDs and hypotheses accordingly, for example, including additional contextual factors such as temperature and public perception of street trees.

At the conclusion of this process, we had developed a preliminary conceptual framework for each intervention and a set of systems-informed research propositions which can be used to guide future empirical evaluation.

Discussion

Statement of principal findings

We outlined the process that we took in applying a systems-informed approach to the development of research propositions in the early stages of two NBS evaluations. We propose a five-step process, entailing: (1) representing the underlying system, (2) developing an understanding of the intervention, (3) identifying links between the intervention and the underlying system, (4) generating systems-informed research propositions, and (5) sense-checking the systems-informed research propositions with subject area experts and stakeholders. The novelty of this approach comes from its application to the evaluation of predetermined interventions, which are introduced without input from the evaluation team and operate on a large scale. The approach we propose here can be applied even when systems-based approaches were not used to develop the intervention itself,

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highlighting a pragmatic process for developing systems-informed research propositions concerning many real-world policy and infrastructure interventions.

We focused on the nonlinearity and feedback aspects of systems thinking and used CLDs as a tool. This approach helped us to consider the underlying system within which each intervention operated (Hawe *et al.*, 2009a), bring together diverse and multidisciplinary findings, identify systemic structures at a higher level of abstraction, and convey complex ideas with members of the project teams from diverse disciplines (e.g. civil engineers, public health experts, ecologists, etc.).

We found that stakeholders and project partners generally had positive feedback around the street-tree project. For example, project partners in one setting commented that they would like to test one of the propositions about street trees, reflecting that their current system of identifying where to plant new street trees relied on a participatory system in which residents voted on location sites. After reviewing the conceptual framework and propositions, this project partner reflected that the voting platform, while encouraging active engagement with residents, may also unwittingly reproduce the "success to the successful" pattern as neighborhoods which have experienced the benefits of street trees already value them more highly and are more likely to advocate for additional trees. She reflected that this may produce unintended inequalities in street-tree distribution.

Street-tree experts noted that the propositions were consistent with expert knowledge and added value by providing potential explanations for surprising or counterintuitive insights in such a way that they could be used to communicate with municipal-level decision-makers. For example, they noted that the importance of resources for street-tree maintenance is well known by tree managers but underappreciated by city-level leaders. They felt the CLD and related propositions made the connections between resources for tree maintenance and outcomes more convincing.

In comparison, we found that stakeholders and project partners were interested in the process around the wetland-restoration project, but engagement was lower. This may have been because the wetland-restoration project involved a small group of experts in one setting, whereas the street-tree project involved many people with different types of expertise across three settings, increasing the likelihood of engagement. Also, while the street-tree project enabled us to identify research questions that pertained to an ongoing intervention (e.g. street trees are a type of NBS each site was involved with in an ongoing basis), the wetland-restoration project pertained to a singular intervention which was already underway. The process we used to develop these evaluative systems-informed research propositions was time consuming and out of sync with other project needs on the wetland project. For instance, another team independently developed an evaluation-survey instrument to be administered to residents, and we were unable to link the

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research propositions developed here with the framing of the survey because this work was not completed in time and because it represented a substantial departure from a more standard, effectiveness-oriented approach. We did not successfully highlight the value of a complementary systems-informed approach to evaluation in this instance.

This work advances our understanding of the potential role and limitations of qualitative systems thinking in developing research propositions for use in empirical (e.g. nonsimulation) evaluations of predetermined interventions.

Strengths and weaknesses of the study

Using CLDs is often encouraged to show and change the mental models of stakeholders/policymakers; it is rarely held up as a way to change our own thinking and approach in subsequent academic work. However, we found that this process allowed us to identify innovative research propositions and broaden our views around the kinds of questions a systems-informed evaluation may focus on.

We also faced several limitations. First, when the underlying system is identified from the literature, the process involves less engagement with experts and stakeholders than is typical for most CLD applications. This may reduce contextual specificity and stakeholder buy-in. Given ample time, resources and access to relevant stakeholders, it would be valuable to incorporate stakeholders more deeply in earlier stages of the process (Coletta *et al.*, 2021). It may be especially useful to adopt a community-based system dynamics approach to the development of these research propositions, where feasible, as this is likely to improve the relevance of the overall evaluation to the community of stakeholders (Hovmand, 2014). However, we were not able to do this in the context of either NBS intervention given time and resource constraints.

Second, we chose to focus on qualitative CLDs and did not engage in any quantitative system dynamics simulation modeling. While CLDs can illuminate feedback loops and simple behaviors over time, it is challenging to interpret how multiple feedback loops interact, or how the relative strength of different feedback loops may change over time without the use of computer-based system dynamics modeling. Doing so in the future may add further nuance and insight to the systems-informed propositions that are developed through this process. However, research teams will have to assess the potential trade-offs in terms of time and resource at the evaluation development stage, and in many cases using qualitative CLDs may be a pragmatic decision.

Finally, the time required to develop these propositions is substantial and extends the overall time for evaluation. Since subsequent components of the evaluation are contingent on this process, ensuring that the propositions

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developed are used to frame components of the evaluation requires strong overall coordination, longer than usual timeframes, and a multidisciplinary team with a commitment to adopting a systems perspective. We struggled and were ultimately unable to develop systems-informed research propositions in time for them to be incorporated within the wetland-restoration empirical evaluation. However, with structured guidance and greater experience with CLDs, the time required could be substantially decreased and the potential value added more clearly elaborated.

In relation to other studies

There are emerging examples of systems-informed empirical evaluations, such as the ongoing evaluation of the Lifestyle Innovations Based on Youth Knowledge and Experience (LIKE) program in Amsterdam (Luna Pinzon *et al*., 2022). The authors developed a framework (the ENCOMPASS framework) to provide guidance on how to conduct an applied systems-informed evaluation. They identified five interconnected stages: "(1) adopting a system dynamics perspective on the overall evaluation design; (2) defining the system boundaries; (3) understanding the preexisting system to inform system changes; (4) monitoring dynamic programme output at different system levels; and (5) measuring programme outcome and impact in terms of system changes" (Luna Pinzon *et al*., 2022, p. 1). However, the authors developed this framework to apply to the development and evaluation of a new program, where the research team is able to actively develop and contribute to the nature of the intervention. Garcia *et al*. present an alternative "Action-oriented framework for systems-based solutions aimed at childhood obesity prevention," which includes guidance on how to envision and enact systems-wide change (Garcia *et al*., 2021). This framework involves a six-step process and entails the following steps: "(1) foster multisectoral team; (2) map the system, its context, and drivers; (3) envision system-wide changes; (4) effect system-wide changes; (5) monitor, learn, and adapt; and (6) scale and sustain" (Garcia *et al*., 2021). This framework also addresses a context in which research teams have some agency in co-envisioning and co-effecting change within the system. We found ourselves in a different position with the predetermined policy and infrastructure interventions described above. Unlike proposed systems-wide program activities which can be codeveloped with the research team, we considered predetermined interventions and were tasked with evaluating them through a systems-informed lens. Thus, while there are many similarities between the process we describe here and the ENCOMPASS and action-oriented frameworks, there are also some necessary departures given our unique application.

Our approach shares much in common with the qualitative-process evaluation framework put forth by McGill *et al*. (2020), which emphasizes describing the overall system (Phase 1) and analyzing the system undergoing

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change (Phase 2). The output of our process aligns with Phase 2, Step 1: "Define questions with hypotheses from Phase 1; operationalize relevant complexity to focus on how the system is changing following intervention implementation" (p. 16).

Meaning of the study

This approach may be well-suited to developing propositions to guide a multicomponent evaluation of a predetermined intervention, at least under certain conditions. It seemed that the value of this process was clearer in the street-tree application, in which we aimed to develop general research propositions which could be applied to an ongoing NBS intervention across many possible sites. In comparison, the approach seemed less useful in the wetland-restoration application, in which we aimed to develop specific research propositions about one particular instance of an intervention, which was already ongoing and for which the timelines regarding the development of evaluation instruments were too tight to be informed by this work. This may be partially addressed by greater familiarity with systems thinking; the time required could be substantially reduced were we to repeat this exercise knowing what we know now. The resistance to incorporating a systems perspective throughout the overall evaluation highlights the importance of earlier engagement with project partners. Adopting a participatory group model building or even community-based system dynamics approach (Hovmand, 2014) may have proved fruitful in this regard.

The use of systems thinking, and especially the abstraction to a simpler CLD combined with the integration of systems archetypes, helped us to develop novel systems-informed research propositions. This process changed our understanding of the interventions in profound and unexpected ways. Testing the related hypotheses may require integration across disciplines that have not previously been linked and requires engagement with a wide range of stakeholders. Finally, building on a preexisting CLD highlighted the value of developing and publishing systems-informed evidence syntheses which can be built on in future projects.

We focused on two NBS interventions here, but it is likely that a similar process may be useful in developing research propositions around other large-scale predetermined interventions, particularly when the research team is familiar with systems methods and can produce these propositions in a timely manner, or when the intervention is ongoing across several settings. We suggest early engagement around the potential contribution of a systems perspective with all stakeholders involved in the evaluation, to ensure that systems-informed research propositions can be integrated within the overall evaluation design.

Finally, we have used the term "research proposition" because we find that this allows us to move from the general systems-informed question of "how have the intervention and system adapted to one another?" towards

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specific and conceptually "thick" statements, which can be operationalized as refutable (i.e. testable) hypotheses within an evaluation. This lends some direction and guides research teams towards a systems-informed analysis. It remains to be seen to what extent this is useful in evaluations that are carried out to completion, and this would be a promising area for future work in the systems/empirical evaluation sphere.

Conclusions

While there have been many calls for a systems-informed approach to evaluation (Moore *et al*., 2018; Petticrew *et al*., 2019; Rutter *et al*., 2017), there are fewer worked examples or step-by-step methodological guidance around how to operationalize these calls. While other systems-oriented evaluation frameworks describe processes that are appropriate when the research team has some influence over the activities that are developed and implemented (Garcia *et al*., 2021; Luna Pinzon *et al*., 2022), we propose this approach for evaluation teams that are tasked with considering predetermined interventions, over which they have no influence or control.

The approach summarized here helped us to produce novel research propositions and lay the foundation for evaluation designs informed by a systems perspective. We suggest that investing time and resources in the development of systems-informed research propositions at the start of an evaluation may enhance our ability to produce policy-relevant research insights, especially by considering feedback loops between drivers of an intervention and intervention impacts. This may support the introduction and maintenance of NBS (and other predetermined large-scale interventions) that address a range of health and sustainability issues and reduce the risk of unintended consequences of interventions that may affect their successful implementation through a holistic approach in the evaluation design stages.

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Biographies

Miriam Alvarado has a background in Economics and International Development Studies from the University of California, Berkeley, and a Master of Public Health (MPH) focused on health metrics from the University of Washington, Seattle. Miriam was a Post-Bachelor Fellow at the Institute of Health Metrics and Evaluation and worked on the Global Burden of Disease 2010 as well as social determinants of health. Miriam was a Fulbright Scholar and conducted research on gendered physical activity in Barbados. Prior to joining CEDAR, Miriam was working with the University of the West Indies on physical activity promotion, regional health inequalities, and chronic disease prevention. In 2020 she completed a Gates Cambridge funded PhD with the Population Health Interventions program. Her research focus was an evaluation of the sugar-sweetened beverage tax implemented in Barbados in 2015, supervised by Dr. Jean Adams and Professor Nigel Unwin. Following her PhD, she worked as a postdoctoral researcher at the University of Exeter.

Dr. Jo Garrett is a postdoctoral research associate valuing nature-based solutions in monetary terms for the REGREEN and RECONECT projects. Jo's research is focused on the interactions between human health, well-being, and nature, previously working on a collaboration with the Chinese University of Hong Kong on coastal environments and human health and the Horizon 2020 funded BlueHealth project. Much of Jo's work applies quantitative data analysis to large-scale survey and/or geographical datasets. Jo has always been interested in the marine environment and completed her BSc in Marine Biology at Swansea University in 2010 followed by an MSc in Environmental Biology. She joined the University of Exeter in 2012 to carry out a European Social Fund PhD with the title "Interdisciplinary study into the effect of a marine renewable energy testing facility on underwater sound in Falmouth Bay." This involved recording underwater sound over 18 months during trialing of the Fred Olsen wave energy converter, BOLT Lifesaver, at the Falmouth Bay Test Site. Jo has also worked on a number of different research topics with Professor Kevin Gaston including light pollution, ecosystem services in Cornwall, and urban greenspace.

James Fullam, after completing a primary degree in zoology, pursued a PhD in the emerging area of health literacy. Subsequently he worked with an industry-led research group that focused on costing and mapping dementia-care pathways and also coordinated a program for building research capacity amongst specialized and advanced nurses in Ireland. Prior to moving to the

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ECEHH, James worked as a research fellow with The NIHR Collaboration for Leadership in Applied Health Research and Care South West Peninsula (PenCLAHRC). James' research interests span a broad range of public health and health services research with a focus on evidence synthesis and the development and conduct of complex interventions for human health. Latterly James has been able to merge his interest in complex interventions development with an interest in the use of nature-based interventions, as therapeutic interventions for mental health on the MRC-funded Nature on Prescription Project. Translating research into resources that are practical and valuable in the real world is a strong motivation in Dr. Fullam's work, the most recent example being the production and release of a Nature on Prescription handbook for providers of nature-based interventions.

Dr. Rebecca Lovell's research focuses on understanding the ways people can benefit from proximity to and contact with "natural" environments. She is specifically interested in the health and well-being benefits of higher quality and biodiverse spaces and places. Relationships between the environment and health are complicated, multifactorial, and highly contextual. Dr. Lovell and colleagues are developing the use of complex research designs which use cross-disciplinary multimethod research approaches. Dr. Lovell is particularly interested in how we can integrate both traditional and novel qualitative and quantitative methods to unpick the specific impacts of natural environments to people's health and well-being.

Dr. Cornelia (Conny) Guell is a medical anthropologist researching practices and policies related to physical activity and nutrition, including active living infrastructure and food systems. Conny's research focuses on how healthy living is shaped across the lifecycle, within population groups, and in and by various sociocultural, historical, political, and economic contexts. Her work is based in the United Kingdom, the Caribbean region, and elsewhere. Dr. Guell is the ECEHH's interim Co-Director with Dr. Ben Wheeler.

Dr. Tim Taylor's main research interest is in the valuation of environment and health endpoints in policy analysis and in the use of economic instruments to improve the environment. Dr. Taylor has experience in stated preference (contingent valuation, choice experiments) and revealed preference (hedonic pricing) methods. A particular interest is the economic assessment of climate change policy, particularly adaptation. He has acted as a consultant in the application of cost–benefit and cost-effectiveness analysis for a range of sectors including waste, forestry, and energy.

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Prof. Ruth Garside is a social science researcher specializing in systematic review and evidence synthesis. She has over 20 years' experience using quantitative and qualitative research methods to investigate a range of health and social-care questions. Her work has informed policy customers including WHO, the National Institute for Health and Clinical Excellence (NICE) and the Home Office. Prof. Garside is particularly interested in using a broad range of evidence to investigate complex public health issues and has a particular interest in methods of synthesis for qualitative research. She coordinates evidence synthesis across the streams of ECEHH research and develops these methods within environment and human health.

Marianne Zandersen, Dr.rer.pol., is a senior researcher in environmental economics in the Environmental Social Science and Geography Section, Department of Environmental Science, Aarhus University. Marianne has 20 years of experience working with research and advisory services across Europe, Africa, and Asia. Marianne focuses on environmental and behavioral economics in the fields of urban and peri-urban systems, nature-based solutions, climate change, and ecosystem management across different habitats. This includes analyses of perceptions, values, willingness to pay for improvements, or willingness to accept a deterioration of conditions and incentive-based mechanisms such as payment for ecosystem services, taxes or subsidies to reduce externalities or enhance the optimal delivery of social goods such as clean air, water, and biodiversity. Marianne has participated in more than 40 national and international research and advisory projects over the past 19 years. She is currently the coordinator of the H2020 project "REGREEN" (2019–23), the coordinator of Climate Society and Health at the iClimate – Aarhus University Interdisciplinary Centre for Climate Change, principal investigator from Aarhus University of the Danida funded CREAM project (2019–24) and project leader from Aarhus University in the European Topic Center for Climate Change Impacts, Vulnerability and Adaptation of the European Environment Agency (EEA ETC/CCA), currently contributor to two EEA reports: "Urban Adaptation to Climate Change in Europe" and "Nature-based solutions to Climate Change Adaptation and Disaster Risk Reduction."

Dr. Benedict W. Wheeler is a quantitative health geographer and environmental epidemiologist. His research focuses on adverse and beneficial impacts of the environment on public health and well-being, especially green/blue space, physical activity and mental health at population scale; applications of GIS and spatial analysis to link and analyze large-scale health and environmental datasets; and environmental and sociospatial health inequalities. He works

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extensively with large, collaborative interdisciplinary research project teams addressing these issues, in projects supported by funders including ESRC, NERC, NIHR, Wellcome Trust, and the European Commission. Ben works with a wide range of partners to translate evidence, especially on links between natural environments and health, to inform public health and environmental policy at local, national, and international scales.

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