Alvarado, M. R., R. Lovell, C. Guell, T. Taylor, J. Fullam, R. Garside, M. Zandersen, and B. W. Wheeler. 2023. Street trees and mental health: developing systems thinking-informed hypotheses using causal loop diagraming. Ecology and Society 28(2):1. https://doi.org/10.5751/ES-14013-280201

Synthesis

Street trees and mental health: developing systems thinking-informed hypotheses using causal loop diagraming

Miriam R. Alvarado [1,2], *Rebecca Lovell* [1], *Cornelia Guell* [1], *Tim Taylor* [1], *James Fullam* [1], *Ruth Garside* [1], *Marianne Zandersen* [3] and *Benedict W. Wheeler* [1]

ABSTRACT. We considered the relationship between street trees and mental health with the aim of developing systems thinking-informed hypotheses to improve the implementation and evaluation of this popular nature-based solution (NBS). We integrated qualitative and quantitative evidence using causal loop diagraming (CLD), and then further analyzed and extended these diagrams with the aid of systems archetypes to identify key system structures. From these CLDs, we identified three systems thinking-informed hypotheses: 1) although there are many ways in which street trees may improve mental health, tree health is critical in realizing many of these benefits and minimizing dis-benefits; 2) communities which have benefited from street trees in the past are more likely to be able to advocate for additional trees, further entrenching historical inequities in street tree distribution; and 3) efforts to address these inequities through new tree planting initiatives may ultimately fail or even exacerbate existing challenges if they do not include sustained resources for tree maintenance, with direct and indirect impacts on inequities in mental health. Using a systems thinking lens was a useful way to deeply consider a purported but under-theorized co-benefit of a popular nature-based solution and identify policy-relevant hypotheses to guide future research.

Key Words: *causal loop diagram; health and well-being; mental health; street trees; systems science; urban planning*

INTRODUCTION

Street trees and the potential for mental health benefits

Cities around the world are facing significant and overlapping challenges around urbanization, climate change, and health and social inequalities (Grimm et al. 2008, Corburn 2017, Heaviside et al. 2017, Orimoloye et al. 2019). Street trees are a type of nature-based solution (NBS) with the potential to reduce the urban heat island effect, improve air quality, and increase physical activity (Roy et al. 2012, Andersson-Sköld et al. 2015, Mullaney et al. 2015, Salmond et al. 2016, Wolf et al. 2020). In selecting street trees as an NBS of focus, we were guided by stakeholders in a multicomponent 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), who identified street trees as a priority NBS across the project's three European Urban Living Labs (Aarhus, Denmark; Paris, France; Velika Gorica, Croatia).

We follow Salmond et al. in defining street trees broadly as "trees along streets," including trees along the sides of major roads, in medians, and along residential streets but excluding trees in other urban spaces. Interest in the climate adaptation potential of street trees is growing, and local and national campaigns have been launched with the aim of preserving existing street trees and planting large numbers of new street trees (Rae et al. 2010, Salmond et al. 2016, Watkins et al. 2017, Werbin et al. 2020).

Street trees may impact mental health, for example, by reducing stress through contributing to a more pleasant living environment or by increasing Seasonal Affective Disorder through reducing ambient light in the winter (de Vries et al. 2013, Salmond et al. 2016). We define mental health as being "a state of well-being in which an individual realizes his or her own abilities, can cope with the normal stresses of life, can work productively, and is able to make a contribution to his or her community" (World Health Organization 2018). Street tree density has been shown to have a protective effect on mental health, especially among individuals with low socioeconomic status (SES) (Marselle et al. 2020). Given that the burden of disease related to mental ill-health is typically higher in cities (Vigo et al. 2016, Gruebner et al. 2017, Okkels et al. 2018), and projected to increase globally (Foreman et al. 2018), understanding how to maximize the benefits of street trees for mental health will enable city governments to make the most of this purported co-benefit of street trees.

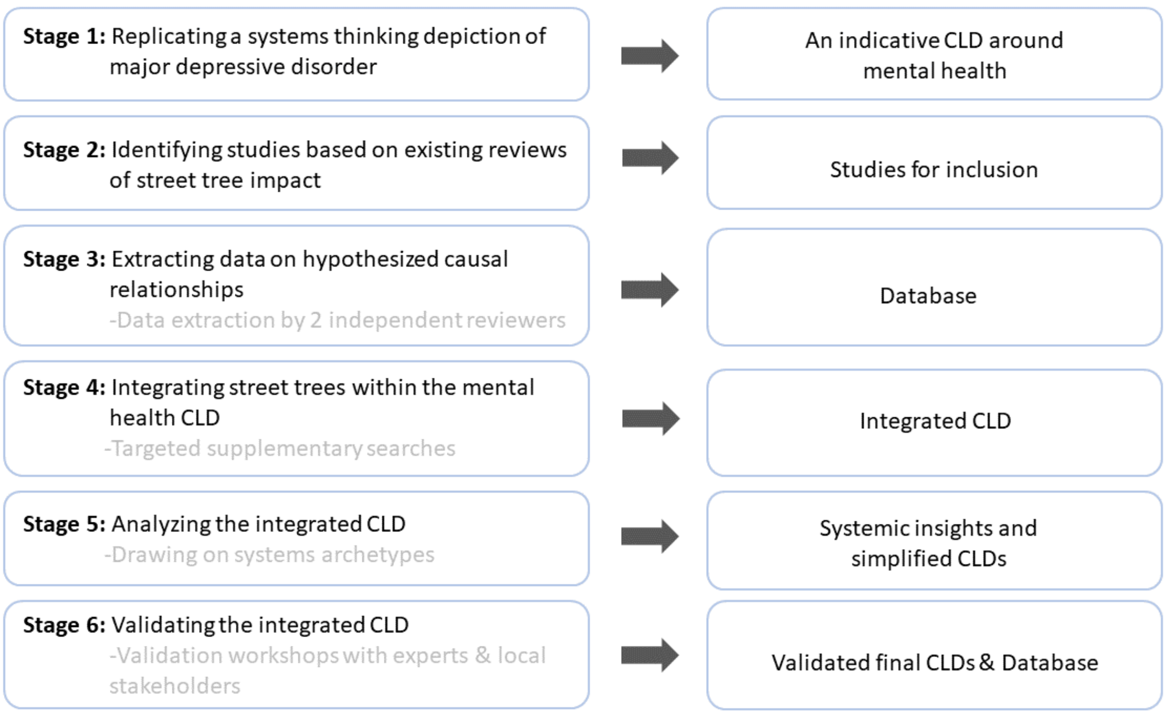
Rationale for taking a systems thinking approach

Systems thinking provides a series of tools specifically designed to consider multiple outcomes, feedback loops, and unexpected consequences (Sterman 2000, Meadows and Wright 2009, Rutter et al. 2017, Petticrew et al. 2019, McGill et al. 2021). Within this perspective, an intervention (such as a street tree planting program) interacts with and impacts an underlying system, rather than producing a linear impact independent of the system (Petticrew et al. 2019). Instead of asking whether street trees "work" to improve mental health, a systems perspective leads us to ask a different question: How may street trees impact, and be impacted by, the underlying system around mental health over time (Petticrew et al. 2019, Skivington et al. 2021)? By adopting this approach, we also hope to be able to identify potential unexpected consequences of street trees for mental health, which in turn may enable municipal stakeholders to preempt any undesirable impacts and maximize potential benefits.

Causal Loop Diagrams (CLDs) are one systems thinking tool, which were developed to map and visualize hypothesized causal relationships and feedbacks between components of a system (Sterman 2000). CLDs provide a useful way of visually summarizing system structures and can be used in conjunction with systems archetypes to identify dynamic properties of an intervention within a system (Kim 1994).

[1]European Centre for Environment and Human Health, University of Exeter Medical School, [2]MRC Epidemiology Unit, University of Cambridge, [3]Department of Environmental Science, iClimate Interdisciplinary Centre for Climate Change, Aarhus University

Fig. 1. Summary of study method stages.



Aim

We aim to develop systems thinking-informed hypotheses around the relationship between street trees and mental health, taking into account unintended consequences and feedback patterns over time.

METHODS

Figure 1 summarizes the approach we took, drawing on systems thinking best practices (Sterman 2000, Meadows and Wright 2009).

Table 1 provides a glossary of terms used.

Stage 1: Replicating a systems thinking depiction of mental health

We followed guidance to consider the underlying system before considering how an intervention may impact the system (Hawe et al. 2009, McGill et al. 2020). We conceptualized "mental health" as an outcome of a complex adaptive system comprised of multiple simultaneous interrelated determinants (e.g., socioeconomic status, physical health, stress, sleep problems, etc.) (Wittenborn et al. 2016, Langellier et al. 2019).

To describe this system, we drew on a systems thinking-informed CLD around the determinants of negative affect and major depressive disorder (MDD) developed by Wittenborn et al. based on the results of a systematic review (Fig. 2A for a simplified version) (Wittenborn et al. 2016). Negative affect entails feelings of "anxiety, sadness, fear, anger, guilt and shame, irritability, and other unpleasant emotions" (Stringer 2013) and is a key dimension of MDD when experienced over a period of two weeks or more (Gellman and Turner 2013). We were not able to identify an evidence-based CLD of mental health more broadly (Langellier et al. 2019), but many of the pathways in Wittenborn et al.'s model (e.g., economic status and stress, physical health, and physical inactivity, etc.) contribute to broader conceptions of mental health (Dolan et al. 2008), and a high ratio of positive to negative affect has been associated with flourishing mental health, while high levels of negative affect are associated with diminished mental health (Diehl et al. 2011).

Wittenborn et al. use the node "dysfunctional behaviors" to capture a wide range of behaviors, including medication non-adherence, poor diet, and perpetrating domestic abuse. However, the potential interactions and upstream determinants of this wide range of behaviors may be obscured through this aggregation. In addition, additional factors are absent, such as intergenerational trauma (Sangalang and Vang 2017, Barlow 2018), and a wider range of physiological factors. Acknowledging these limitations, we made the pragmatic decision to use the Wittenborn model as a proxy for broader determinants of mental health, given our hypothesis-generating research aim. We adapted their model with a focus on the social and economic dimensions. For example, while the Wittenborn model includes a pathway from physical inactivity to cortisol and then to sleep problems; we simplified this chain for our purposes, linking physical activity directly with sleep problems.

Stage 2: Identifying empirical studies

We were interested in identifying empirical studies which assessed the relationship between street trees (including determinants and impacts of street trees) and components of the system identified in Step 1 around mental health. Given our research aim to

Table 1. Glossary of terms used.

Term	Definition
Causal loop diagram	A qualitative systems thinking approach, consisting of a visual representation of relationships between variables, allowing for feedback loops and delayed impacts over time (Sterman 2000, Meadows and Wright 2009).
Polarity	The direction of a causal relationship between two variables. A "+" indicates that both variables move in the same direction whereas a "-" indicates an inverse relationship (Sterman 2000).
Feedback loop	A combination of connected variables connected in a circular sequence. Feedback loops may be reinforcing or balancing (Sterman 2000, Meadows and Wright 2009).
Hypothesized causal relationship	We use this term to refer to empirically-based associations that are thought to reflect a cause-effect relationship. We emphasize that these are hypothesized causal relationships rather than definitive casual claims.
Complexity-informed hypothesis	We use this term to refer to hypotheses that take into account aspects of complexity (e.g., emergence, feedback loops, delayed impacts). These higher-level hypotheses are derived from a systems-based understanding of a phenomenon and move beyond more linear "X causes Y" hypotheses.
Systems archetype	Specific combinations of feedback loops within a CLD which have been observed in many different types of systems and are associated with predictable patterns (Kim 1994).

generate systems thinking-informed hypotheses, a traditional systematic review was neither appropriate nor feasible. Instead, we followed Lorenc et al. (Lorenc et al. 2012, 2014) and focused on identifying and synthesizing a wide range of relevant conceptual material, prioritizing the inclusion of evidence from a range of disciplines.

We began with several recent reviews of street tree impacts (Mullaney et al. 2015, Salmond et al. 2016, Wolf et al. 2020) and used these to identify relevant references, using a citation-chasing approach to identify primary empirical studies (both quantitative and qualitative) (Cooper et al. 2017). We supplemented this approach with targeted Google Scholar searches to identify evidence around intermediate links. For example, we found evidence linking street trees with changes in temperature and subsequently conducted a targeted search to identify evidence about the relationship between temperature and sleep problems (Rifkin et al. 2018). This mirrors a process used previously in the development of conceptual frameworks (Schram et al. 2017).

After several studies had been identified to provide evidence for a given hypothesized causal relationship, we focused attention on other relationships, prioritizing breadth and diversity of evidence. We also consulted with several senior academic researchers with expertise around street trees to identify additional relevant references.

Stage 3: Extracting data

For each included study, we extracted data on the following:

- Cause
- Polarity (+/-) of relationship
- Effect
- Delay (yes/no) (e.g., is there a 5+ year lag between the cause and effect?)
- Evidence type (empirical, review finding, assumption)
- Excerpt (to illustrate the hypothesized causal relationship)

The data extraction form was designed to enable translation into causal loop diagrams in Stage 4. Data were extracted using a standardized Excel template (Deegan 2009) by one member of the study team (MA), and every relationship was independently reviewed by a second member of the study team (RL, BW, TT, CG, JF). Disagreements were resolved through discussion. Following Lorenc et al., we broadly considered relevance and rigor, drawing on an approach informed by realist synthesis (Pawson et al. 2004, Lorenc et al. 2012, 2014).

Stage 4: Extending the mental health CLD

We conceptualized street trees as an exogenous intervention (i.e., an external influence) within the system described in Stage 1. We integrated the hypothesized causal relationships around street trees and their determinants/impacts with Wittenborn's model. In some cases, there were direct connections (e.g., between street trees and stress, a key component of the mental health model) (de Vries et al. 2013), and in other cases, connections were indirect (e.g., the impact of street trees on temperature and of temperature on sleep problems, another key component of the mental health model).

Stage 5: Generating systems thinking-informed hypotheses

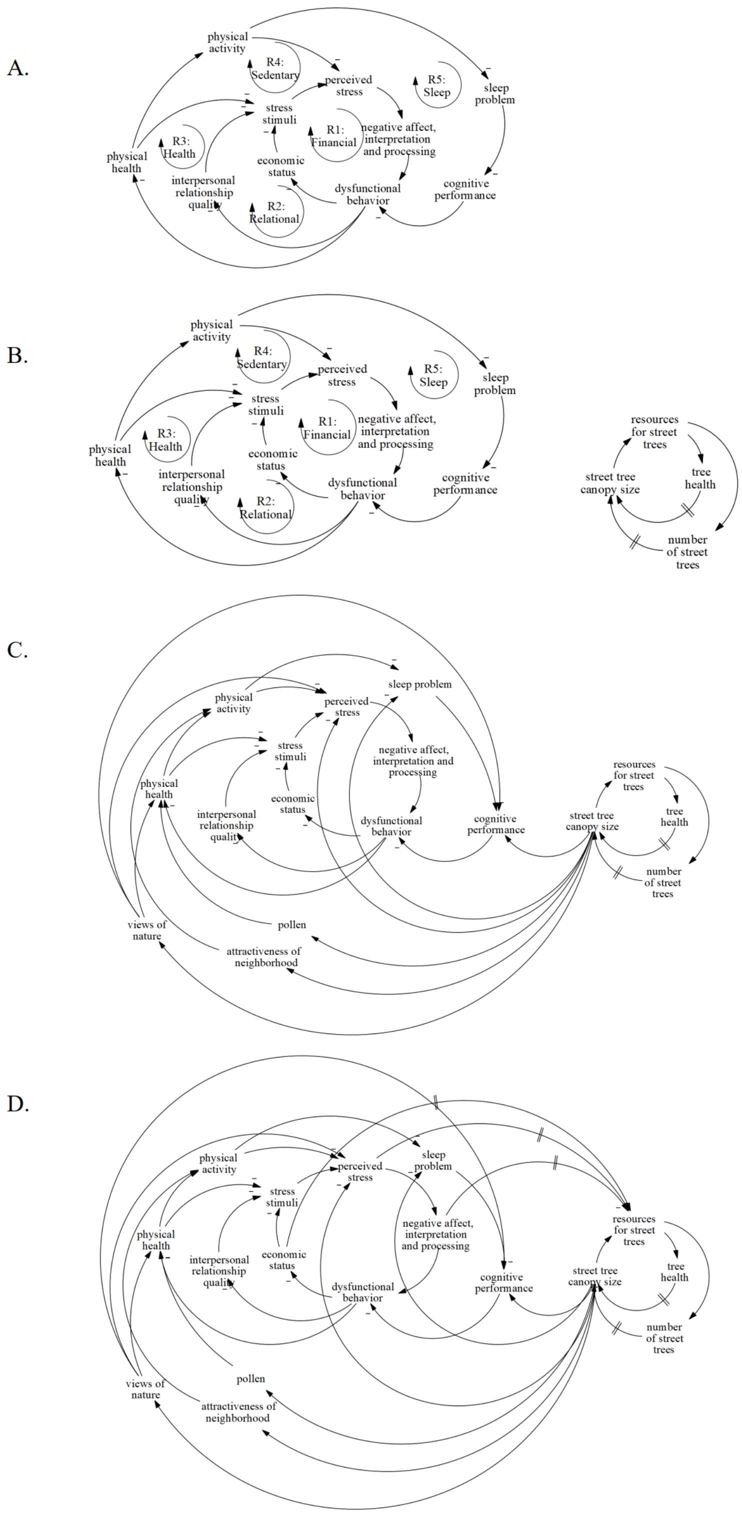
We used the final CLD and systems archetypes to develop systems thinking-informed hypotheses about the relationship between street trees and mental health over time. We asked ourselves the following questions: How would key variables in the CLD change over time? How would these changes over time vary under different starting conditions? We developed qualitative behavior over time graphs (Kim 1994) of key variables to reflect our hypotheses and then interrogated the drivers of these patterns.

We also used systems archetypes (Kim 1994, Wolstenholme 2004) to consider various aspects of the final CLD. Systems archetypes reflect patterns of feedback loops which can be found in many types of systems, and which can be used as diagnostic tools for understanding aspects of a complex system (Kim 1994). For example, we drew on the implication of a "fixes that fail" archetype, which suggests that over time "the problem symptom returns to its previous level or becomes worse" (Kim 1994).

Stage 6: Validation

Finally, we shared the database and CLDs with street tree experts and incorporated feedback in iterative revisions. Representatives (municipal planners, ecologists, and regional development staff) from each of the three European REGREEN Urban Living Labs were asked to reflect on the early results and identify ways in which they did or did not reflect local experiences with street trees in each city. This feedback was used to further revise the CLDs.

Fig. 2. Panel of street tree and mental health CLD progression. Link polarity is (+) unless otherwise shown. The links represent <u>hypothesized</u> causal links. The hypotheses represented by these directional arrows and feedback loops are based on diverse evidence types (many of which cannot prove causality directly) and are intended to be used as the basis of future research.



RESULTS

We summarize the process of developing the CLDs briefly and then focus on key findings based on the validated CLDs.

Stage 1: Replicating a systems thinking depiction of mental health

We present a simplified, adapted version of Wittenborn et al.'s causal loop diagram Figure 2, Panel A (Wittenborn et al. 2016). We take this model as a starting point and focus on extending it by integrating evidence around street tree determinants and impacts in Stages 2–4.

Stage 2: Identifying empirical studies

We identified 77 papers about street trees (and their impacts/determinants) and mental health (Appendix 1).

Stage 3: Extracting data

We extracted data on 94 hypothesized causal relationships (Appendix 2: Table 1). In addition, we made assumptions about a limited number (n=17) of relationships. For example, we assumed that tree vandalism reduces the attractiveness of a neighborhood given the well-established "broken windows theory," (Wilson 1982) although we did not specifically find evidence on this. These relationships are clearly tagged as "assumption" within the database.

Stage 4: Extending the mental health CLD

We used this database to extend Wittenborn's model and developed a detailed CLD with 128 links connecting 69 variables (94 links from the street tree evidence, 17 from Wittenborn et al.'s model, and 17 assumptions). The full CLD can be viewed and interrogated on the web using a standard browser (https://kumu.io/ecehh/street-trees-mental-health-overall-causal-loop-diagram-18d0) and has also been reproduced in Appendix 3, Figure 1.

Using this detailed CLD, we identified 20 interconnected pathways through which trees may have a beneficial effect on mental health (Appendix 4: Table 1). We categorized these broadly based on the three domains of the pathways by which nature contributes to health as identified by Markevych et al. as either 1) reducing harm (e.g., reducing exposure to environmental stressors), 2) restoring capacities (e.g., restoring attention or stress recovery), or 3) building capacities (e.g., encouraging physical activity or social cohesion) (Markevych et al. 2017).

We also identified at least eight pathways through which street trees may have a negative impact on mental health (Appendix 4: Table 2). We categorized these broadly, considering the inverse of the domains identified by Markevych et al. (i.e., increase harm, reduce capacities, prevent capacity building) (Markevych et al. 2017).

Stage 5: Generating systems thinking-informed hypotheses

For ease of interpretation, we present somewhat simplified CLDs here (Fig. 2, Panels A–D). Figure 2 Panel A reflects our adapted version of Wittenborn's model and shows how multiple reinforcing loops contribute to increased negative affect. In Panel B, we introduce a simplified representation of a street tree system, highlighting that street tree canopy size is driven both by tree health (Blunt 2008, Ely 2010) and overall number of street trees. Both of these relationships occur over a longer time horizon (e.g., it takes time for trees to grow to maturity), which is indicated by the delay marks (double perpendicular bars) within the CLD (standard notation). Tree health is critical for both increasing the canopy size (e.g., stressed trees do not grow very well or quickly) and for maintaining the total tree stock (e.g., stressed trees often have shorter lifespans).

Resources for street trees are required to maintain street tree health. Unlike trees in natural settings, street trees require support to thrive in otherwise challenging urban conditions. As one forester summarized:

> *A lot of people think that planting a tree is simple - dig a hole in the ground and walk away - well then you're doomed from the beginning. Urban trees have a tough life. They need planning and long-term care and commitment.* (Shcheglovitova 2020)

Resources for street trees can also lead to the planting of additional trees, increasing the total number of trees (reflected in the simplified system in Panel B).

Many of the benefits of street trees are linked to tree-canopy size (e.g., cooling effects (Rahman et al. 2011), noise reduction (McPherson et al. 2002), shade (Shashua-Bar et al. 2009), etc.). In Panel C, we highlight some of the direct and indirect pathways through which the street tree canopy size may impact negative affect and determinants of mental health in the Wittenborn et al. model. For example, street trees have been hypothesized to reduce negative affect directly, and also to improve cognitive performance, reduce sleep problems, and reduce perceived stress. The relationships shown here are only a subset of those represented in the detailed model (Appendix 3: Fig. 1)

In addition, street trees have been hypothesized to impact intermediary factors which then impact factors in the Wittenborn et al. model. For example, street trees may increase the attractiveness of a neighborhood, leading to increased walkability and thus increased physical activity. Street trees may increase views of nature, which in turn have been shown to improve physical health, reduce perceived stress, and improve cognitive performance. Finally, some impacts of street trees may also have a negative effect. For example, street trees may increase pollen, increasing allergies, and decreasing physical health and well-being. However, appropriate management can preempt many of the risks associated with street trees (e.g., planting appropriate species selection to reduce pollen, proactive pruning to reduce the risk of tree limb falls, etc.) (Brindal and Stringer 2009, Cariñanos and Casares-Porcel 2011, Trees and Design Action group 2014).

We have not shown all of the ways in which street trees may impact the Wittenborn et al. model here - for the complete representation, refer to Appendix 3, Figure 1.

Finally, in Panel D, we highlight the ways in which factors from the Wittenborn et al. model may feed into the availability of resources for street trees, in effect closing the loops between street trees and mental health. Resource availability for trees is in part determined by whether trees are seen as a valuable investment by residents and decision-makers. As people experience the benefits of street trees (not only in relation to negative affect, but also in terms of reductions in perceived stress, increased economic status through property values, increased interpersonal relationships through community cohesion, etc.), support for street trees may increase, justifying additional resource allocation. These impacts likely occur over a longer time horizon.

We analyzed the final CLD, drawing on systems archetypes to guide us in identifying deeper patterns. We identified or further explored the following hypotheses:

1. For street trees to impact mental health, the health of the trees themselves is critical.
2. Historical disparities in street trees are self-enforcing.
3. Uneven maintenance of street trees undermines tree-planting interventions, exacerbating mental health inequities.

We describe each hypothesis in more detail below.

Hypothesis 1: For street trees to impact mental health, the health of the trees themselves is critical.

As noted, for the positive impacts of street trees on mental health to be realized, the health of street trees is critical. As Widney et al. demonstrate, in a study of three U.S. cities, without intervention to increase the survival rate of street trees over time, premature tree mortality undermines the beneficial potential of street trees (Widney et al. 2016). Widney et al. inventoried 10%+ of all street trees planted between 2009–2011 in Detroit, Philadelphia, and Indianapolis, and calculated the annual and cumulative survival rates after 3–5 years (only 60–80% of trees were alive). Based on a modeling analysis, they highlighted that without improvement in the survival rate, only 40% of planted trees would be alive after another ten years, severely limiting the monetary benefits conferred by mature trees. While Widney et al. focused on benefits in terms of property value, energy savings, carbon, air quality, and stormwater effects, a similar pattern is likely to occur around mental health benefits.

As Shcheglovitova summarizes:

> *... planting trees means that tree needs must also be considered to some extent as well. Trees will not care for humans by attending to their needs if they are not alive. Tree needs and human needs are entangled as trees take on the role of active providers of care.* (Shcheglovitova 2020)

Hypothesis 2: Historical disparities in street trees are self-enforcing

Since street trees provide value to neighborhoods, the historic stock of street trees may have contributed to the increasing affluence of tree-rich neighborhoods. In turn, more well-resourced neighborhoods are more effective at advocating for new trees. The reinforcing loops from street tree canopy to factors in Wittenborn et al.'s model, and then from these factors to resources for street trees (Fig. 2: Panel D) may help to explain the persistence of inequities in street tree distribution over time:

> *For example, a program that responds to resident requests for trees (an "opt-in" program), might actually result in more tree plantings (and subsequently higher future canopy cover) in wealthy neighborhoods where residents have access to information about and resources to take advantage of the program.* (Watkins et al. 2017)

This echoes a "success to the successful" systems archetype in which one group has more access to resources initially, and this leads to higher performance or likelihood of succeeding, which in turn justifies additional resources (Kim 1994).

On the other hand, neighborhoods with historically low levels of street trees are less likely to have experienced their benefits and thus less likely to advocate for or invest in new trees. Where resources for street trees are low, tree health is likely to suffer, resulting in fewer trees and smaller canopies. The stressed trees are less likely to provide benefits, and residents are less likely to experience the value of street trees and in some cases even engage in, or fail to take active steps to prevent, tree vandalism. This has a knock-on effect: where tree vandalism is high, city governments tend to plant smaller (less expensive) trees, which again are less likely to produce experienced benefits (Pauleit et al. 2002). In the UK, residents cited not wanting trees because "they would be destroyed by vandals, wasting council tax payers' money for no benefit" (Hitchmough and Bonugli 1997). In the U.S., some residents have experienced an additional harm from street trees: their contribution to processes of gentrification of neighborhoods (Grove et al. 2018). This negative cost, combined with the lack of perceived or real benefits, makes street trees an unattractive intervention. This difficult to address reinforcing feedback loop may lead to low investments in street trees, with residents unlikely to perceive many benefits of street trees, further eroding future investments.

Differences in mental health and in the systems around mental health (e.g., economic status, perceived stress, dysfunctional behavior, interpersonal relationship quality) are the result of decades or centuries of complex power relations and reflect historic segregation, discrimination, and disenfranchisement. Patterns of street tree distribution and the reinforcing impact on perceived value and investment in trees continues (alongside many other factors) to further entrench these historic disparities (Landry and Chakraborty 2009, Grove et al. 2018).

Hypothesis 3: Uneven maintenance of street trees exacerbates mental health inequities

One apparent solution to address the stark differences in street tree coverage may be to invest in tree-planting programs in disadvantaged neighborhoods (setting aside the concerns about gentrification). However, without provisions for adequate maintenance, this intervention may only exacerbate inequities.

This can be summarized through the lens of a "fixes that fail" systems archetype, in which a problem is seemingly addressed by a solution in the short-term, only to be undermined in the long-term when the "solution" causes an unexpected impact, exacerbating the original problem (Kim 1994). While planting new trees in a deprived area may seem like a promising intervention, in the absence of appropriate resources for tree maintenance, tree health may suffer and eventually lead to increased tree decay/death. Ultimately, this apparent "fix" is temporary and may even exacerbate inequity in trees in low SES neighborhoods.

For example, in Baltimore the official housing strategy is to green "stressed" neighborhoods while prioritizing the provision of ongoing municipal services in "choice" neighborhoods to protect their value (Shcheglovitova 2020). However, this short-term "fix" of planting new trees in deprived neighborhoods backfired without appropriate maintenance:

> *...the effect of a dead tree on a city block is felt by the people who must live with them, especially in those neighborhoods that have experienced other forms of*

disinvestment. Ms Avery [...] remarks on this experience when she tells me about the trees that were planted in front of her home: "They planted them and they're dead. They're dead. You want to be making the neighborhood look better not worse. (Shcheglovitova 2020)

Far from improving mental health, dead or decaying trees may increase stress, worsen social cohesion, make neighborhoods less attractive, and have a dampening impact on many of the other pathways through which street trees may benefit neighborhoods (Appendix 4: Table 1).

Stage 6: Validation

We validated the CLDs and hypotheses with two prominent street tree experts through one-to-one meetings, during which we shared a database with all the identified cause–effect relationships, the detailed CLD, the final CLDs, and the systems thinking-informed hypotheses. We received feedback during these calls and in follow-up correspondence.

We also validated the CLDs with 14 municipal stakeholders from the three European Urban Living Labs (Aarhus, Denmark; Paris, France; Velika Gorica, Croatia), associated with the broader REGREEN project. We presented our early findings in a series of online workshops (one workshop with municipal stakeholders from each setting) and asked for general feedback (e.g., "What do you think?) and more specific feedback (e.g., "Are any factors missing which are important in your setting?"). These discussions led to the inclusion of several additional contextual factors (e.g., differences in temperature, public perception of street trees) and further refinements to the CLDs and hypotheses.

DISCUSSION

Statement of principal findings

We integrated quantitative and qualitative evidence around street trees and mental health to develop hypotheses about the relationship between street trees and mental health over time. These hypotheses have implications for maximizing the potential co-benefits of street trees for mental health, addressing entrenched inequities in street tree distribution, and highlighting the importance of investments in maintenance.

To develop evidence-based systems thinking-informed hypotheses, we integrated evidence from 77 empirical studies with a pre-existing model of MDD. We developed a detailed CLD (reflecting 128 hypothesized causal relationships) as an interim output intended to capture a series of *hypothesized* causal relationships rather than presenting an objective description of proven causal relationships. We presented a simplified version, and used this final CLD to develop three corresponding systems thinking-informed hypotheses.

First, to both optimize benefits and mitigate harms, the health of street trees themselves is critical. Resources for appropriate maintenance are essential for tree health, enabling trees to reach the age and size when many of the benefits to mental health are realized. Second, communities which have benefited from street trees in the past may be best-positioned to advocate for additional street trees and engage in tree stewardship in the present. At the same time, communities with scarce or poorly maintained street trees may not experience any benefits of street trees and limit future investment in trees. This dynamic further entrenches inequities in street tree coverage. Third, targeting low SES neighborhoods for new tree planting may fail if maintenance issues are ignored, potentially exacerbating inequities in mental health and beyond.

Strengths and weaknesses of the study

We used an innovative approach to synthesize insights across a wide range of conceptual material and develop systems thinking-informed theory around the relationship between street trees and mental health.

However, we also faced several limitations. First, we used a wide range of types of material (theoretical, quantitative and qualitative empirical research, case studies, expert opinion, etc.) and the validity and generalizability of findings across this evidence base are likely to vary widely. Rather than using this diversity of evidence to inform assessments of causality, we focused on developing causal hypotheses: proposed claims that remain to be further warranted by future empirical work. The process of identifying and selecting studies and hypothesized causal relationships for inclusion was systematic but necessarily subjective. These are common limitations faced by other attempts to synthesize a wide range of evidence in order to develop systems thinking-informed theory (Lorenc et al. 2012, 2014). Importantly, these CLDs are not intended to make robust empirical predictions, but rather to generate systems thinking-informed hypotheses, which can then be tested empirically and refined or refuted. We extracted excerpts from the studies which underpin each hypothesized causal relationship and report these in detail in Appendix 2, Table 1, in an effort to transparently demonstrate the range of evidence included in the development of these CLDs.

Second, these CLDs do not reflect population or community differences, (such as those between children/adults or across neighborhoods with different area-level SES), in tree type (e.g., between deciduous/coniferous), or according to local climatic or geographical conditions. It is likely that the relationships between trees and mental health vary across these factors in ways in which we were not able to capture (Collier 2020). For instance, tree species vary considerably, with implications for impacts (e.g., temperature, water availability, local climate, cultural acceptability, etc.). Instead of trying to tease apart differences by tree species, we included a broad category "appropriate tree planting and maintenance activities," to acknowledge the importance of locally-tailored species selection. The ways in which street trees produce impacts may also vary seasonally, in ways which may affect various aspects of the Wittenborn et al. model differentially. However, we were not able to explicitly reflect this seasonality in the final CLD.

Third, we used the Wittenborn et al. model as a starting point for conceptualizing the system that produces mental health. However, limitations in this initial model (e.g., the exclusion of factors such as intergenerational trauma and the aggregation of diverse factors into several more generic nodes, such as "dysfunctional behavior") suggest that there may be additional links between street trees and mental health which we did not identify and which may be important in developing holistic, systems-informed hypotheses in this area. Community-based system dynamics (Hovmand 2014) and group model building (Vennix 1999) are examples of systems-informed participatory community-oriented approaches which may help to address these gaps in the future.

Finally, most of the evidence that we drew on comes from North America, Northern and Western Europe, and Australia, and it is unclear to what extent these findings may be relevant in other settings. Even among the regions for which we found more evidence, there are likely to be contextual differences, which we did not identify or reflect in these CLDs. To begin exploring contextual differences, we validated the CLDs with local stakeholders in three European cities. This led to the inclusion of several contextual factors (e.g., differences in temperature, public perception of street trees, etc.), but it was challenging to represent nuanced context-specific pathways without developing an overwhelming, unusable CLD. Reassuringly, the overall themes captured in the CLDs appeared consistent across the three cities considered.

In relation to previous studies

The links between nature and mental health (Kuo 2015, Bratman et al. 2019), urban trees and mental health (Roy et al. 2012, Wolf et al. 2020), and overall benefits of street trees (Mullaney et al. 2015, Salmond et al. 2016) have been documented in a number of reviews. Many of the pathways summarized in Appendix 4, Tables 1 and 2, have been captured previously, albeit not with a specific street tree/mental health focus. However, to our knowledge this is the first systems thinking-informed assessment of how street trees may impact mental health.

This assessment led us to consider the politics of street trees: who benefits, who has experienced benefits in the past, whose trees are maintained, etc., and to contextualize street trees within wider and historical systems, all of which have links with mental health. For us, this highlights the value of taking this wide-ranging, open, and systems-inspired approach. We were surprised by the direction that formulating these hypotheses took us in, and perhaps this reflects the possibilities of bringing together insights across disciplines within a systems thinking framework.

Implications/meaning of the study

The hypotheses developed here have implications for how we design, monitor, and evaluate interventions related to street trees and mental health in urban environments.

For example, given the importance of tree health and tree-canopy size in realizing benefits, for mental health and for many of the other co-benefits associated with street trees, it would be important to develop an indicator that incentivizes investments in tree health (instead of a focus only on absolute numbers of new trees). From a systems thinking perspective, such an indicator may represent a powerful leverage point as a change in the “structure of information flows,” one of the more effective leverage points based on Donella Meadow’s classification (Meadows and Wright 2009). Such changes are especially powerful because they create information feedback loops, whereby city officials are either commended for being “at the top of the list” or motivated to make policy changes if they are shown to fall behind other similar cities. Along these lines, the Lancet Countdown series on health and climate change introduced a new environmental indicator in 2020: using remote sensing to measure green vegetation in large cities and ranking them according to levels of greenness (Watts et al. 2021). While not specifically about street trees, this measure is influenced by tree-canopy coverage more than by the number of new trees, and similar measures may create incentives to align action with the evidence base more closely.

Given the potential benefits of street trees for mental health, there is a strong mandate to find ways to effectively reduce street tree inequities without unintentionally causing other forms of inequity, such as that resulting from gentrification. Lower SES residents may experience the protective effects of street trees on mental health more than their higher SES counterparts (Marselle et al. 2020), and neighborhoods, which have been historically marginalized, may benefit from urban trees more than more privileged neighborhoods (e.g., based on different experiences of industrial pollution and potential remedial benefits of trees) (Vogt and Abood 2020). However, interventions to address differential access to street trees may exacerbate existing inequities if they do not address, at a minimum, street tree maintenance issues. Guidance around a “fixes that fail” archetype suggests that breaking the cycle requires “acknowledging up front that the fix is merely alleviating a symptom, and making a commitment to solve the real problem now” (Kim 1994). This may require deeply considering issues of disenfranchisement, historical legacies, community-based and community-led development, and a collective-impact approach (Vogt and Abood 2020). This is surely a much more ambitious project, but without addressing these root problems, short-term solutions may fail or even compound existing problems.

Finally, identifying ways in which street trees may contribute to the goals of other sectors (e.g., public health, transportation) will be key and may facilitate access to cross-sector resources in line with the expected benefits of street trees (Trees and Design Action group 2014). There is a compelling argument for public health authorities to consider street trees as a health intervention. Street trees may provide an “unintentional daily contact to nature” (Marselle et al. 2020), and their impact on mental health through pathways such as stress reduction or attention restoration may require less agency on behalf of the individual than other types of greenspace (e.g., parks) (Taylor et al. 2015). There have been increasing calls for low-agency population health interventions, which have the potential to prevent illness and minimize inequalities (Adams et al. 2016). With appropriate tree maintenance, street trees may represent such a low-agency intervention with the potential to reduce inequities in mental health. Finally, the restrictions of movement associated with COVID-19 may have increased the impact of street trees on local residents’ mental health, highlighting the need to understand the role trees can play in resilience building.

Future research

All of the hypotheses that we have proposed here can be empirically tested and further refined. For example, tree health, canopy size, or tree quality can be assessed quantitatively as a potential mediator between street tree quantity and mental health impacts. City-level street tree maintenance expenses could be compared or assessed over time and between jurisdictions. Case studies around municipal experiences with advocating for increased maintenance funding would be particularly relevant. A number of disciplinary perspectives and methodological approaches could test and build on the hypotheses put forth here.

CONCLUSION

Overall, we found that street trees have the potential to impact mental health in many ways, including by reducing harm, restoring capacities, and building capacities. Although street trees may also have negative impacts on mental health, many of these negative impacts can be mediated by appropriate tree management practices.

However, many of the beneficial impacts that street trees may have on mental health are contingent on the health of the trees themselves, and relatedly, on the availability of resources for appropriate tree maintenance. There are several systemic structures which we hypothesize produce the patterns we have described here, for example, around inequities in street tree coverage and underfunding of street tree maintenance. We used systems archetypes to develop systems thinking-informed hypotheses around these complex relationships.

In an era when urban trees are increasingly under pressure from densification, prioritization of other infrastructure, and increased negative impacts of climate change, it is all the more important that efforts to promote street trees take into account unintended consequences, feedback loops, and delayed effects. The use of causal loop diagrams and systems archetypes has enabled us to integrate quantitative and qualitative evidence to generate hypotheses that take these dynamics into account, identifying promising and potentially high-impact systems structures and intervention points and offering a critical analysis of some of the bottlenecks and potential leverage points which can be acted upon.

Acknowledgments:

This work was supported by EU Horizon 2020-project REGREEN (Grant Agreement No. 821016). REGREEN includes a focus on three European "Urban Living Labs": Velika Gorica, Croatia, Aarhus, Denmark, and Île-de-France (the Paris region), France. During an early stage of the REGREEN project, representatives from these cities were asked to rank a range of nature-based solutions. Street trees were identified as a priority across all three cities, driving our focus in this study. Later in the process, the same Urban Living Labs took part in validating the integrated CLD of street trees and mental health. The authors would also like to thank REGREEN consortium members from the cities of Aarhus, Denmark (Signe Iversen, Lene Larsen, Sara Kruse Cox, Peter Søgaard, and Hanne Lund Steffensen); the Paris Region, France (Gwendoline Grandin and Marc Barra (ARB îdF, Paris Region Biodiversity Agency), and Mara Sierrajimenez, Anne-Caroline Prévot (MNHN, National Museum of Natural History); and Velika Gorica, Croatia (Marko Ruzic, Sandra Vlašić, Josip Beber, Gordana Mikulčić Krnjaja, and Meri Barisic) in addition to street tree experts (Matilda van den Bosch and Clive Davies (European Forest Institute)) for valuable comments and suggestions. The authors would also like to thank Mark Petticrew for his methodological guidance during an early stage of the project and for reviewing a later draft, Åsa Ode Sang for her input and reviewing an early draft, and the wider REGREEN project team for feedback on the approach and focus.

Data Availability:

The data that support the findings of this study are openly available in the Appendix.

LITERATURE CITED

Adams, J., O. Mytton, M. White, and P. Monsivais. 2016. Why are some population interventions for diet and obesity more equitable and effective than others? The role of individual agency. PLOS Medicine 13(4):e1001990. https://doi.org/10.1371/journal.pmed.1001990

Andersson-Sköld, Y., S. Thorsson, D. Rayner, F. Lindberg, S. Janhäll, A. Jonsson, U. Moback, R. Bergman, and M. Granberg. 2015. An integrated method for assessing climate-related risks and adaptation alternatives in urban areas. Climate Risk Management 7:31-50. https://doi.org/10.1016/j.crm.2015.01.003

Barlow, J. N. 2018. Restoring optimal Black mental health and reversing intergenerational trauma in an era of Black Lives Matter. Biography 41(4):895-908. https://doi.org/10.1353/bio.2018.0084

Blunt, S. M. 2008. Trees and pavements—are they compatible? Arboricultural Journal 31(2):73-80. https://doi.org/10.1080/03071375.2008.9747522

Bratman, G. N., C. B. Anderson, M. G. Berman, B. Cochran, S. de Vries, J. Flanders, C. Folke, H. Frumkin, J. J. Gross, T. Hartig, P. H. Kahn, M. Kuo, J. J. Lawler, P. S. Levin, T. Lindahl, A. Meyer-Lindenberg, R. Mitchell, Z. Ouyang, J. Roe, L. Scarlett, J. R. Smith, M. van den Bosch, B. W. Wheeler, M. P. White, H. Zheng, and G. C. Daily. 2019. Nature and mental health: an ecosystem service perspective. Science Advances 5(7):eaax0903. https://doi.org/10.1126/sciadv.aax0903

Brindal, M., and R. Stringer. 2009. The value of urban trees: environmental factors and economic efficiency. The 10th National Street Tree Symposium.

Cariñanos, P., and M. Casares-Porcel. 2011. Urban green zones and related pollen allergy: a review. Some guidelines for designing spaces with low allergy impact. Landscape and Urban Planning 101(3):205-214. https://doi.org/10.1016/j.landurbplan.2011.03.006

Collier, B. 2020. There's a trauma in loss of connection to nature, we need to stop saying that it's not for us. March 10. http://www.bethcollier.co.uk/theres-a-trauma-in-loss-of-connection-to-nature-we-need-to-stop-saying-that-its-not-for-us/

Cooper, C., A. Booth, N. Britten, and R. Garside. 2017. A comparison of results of empirical studies of supplementary search techniques and recommendations in review methodology handbooks: a methodological review. Systematic Reviews 6 (1):234. https://doi.org/10.1186/s13643-017-0625-1

Corburn, J. 2017. Urban place and health equity: critical issues and practices. International Journal of Environmental Research and Public Health 14(2):117. https://doi.org/10.3390/ijerph14020117

Deegan, M. A. 2009. Developing causal map codebooks to analyze policy recommendations: a preliminary content analysis of floodplain management recommendations following the 1993 midwest floods.

de Vries, S., S. M. E. van Dillen, P. P. Groenewegen, and P. Spreeuwenberg. 2013. Streetscape greenery and health: stress, social cohesion and physical activity as mediators. Social Science & Medicine 94:26-33. https://doi.org/10.1016/j.socscimed.2013.06.030

Diehl, M., E. L. Hay, and K. M. Berg. 2011. The ratio between positive and negative affect and flourishing mental health across adulthood. Aging & Mental Health 15(7):882-893. https://doi.org/10.1080/13607863.2011.569488

Dolan, P., T. Peasgood, and M. White. 2008. Do we really know what makes us happy? A review of the economic literature on the factors associated with subjective well-being. Journal of Economic Psychology 29(1):94-122. https://doi.org/10.1016/j.joep.2007.09.001

Ely, M. 2010. Integrating trees into the design of the city. The University of Adelaide. Adelaide, Australia.

Foreman, K. J., N. Marquez, A. Dolgert, K. Fukutaki, N. Fullman, M. McGaughey, M. A. Pletcher, A. E. Smith, K. Tang, C.-W. Yuan, J. C. Brown, J. Friedman, J. He, K. R. Heuton, M. Holmberg, D. J. Patel, P. Reidy, A. Carter, K. Cercy, A. Chapin, D. Douwes-Schultz, T. Frank, F. Goettsch, P. Y. Liu, V. Nandakumar, M. B. Reitsma, V. Reuter, N. Sadat, R. J. D. Sorensen, V. Srinivasan, R. L. Updike, H. York, A. D. Lopez, R. Lozano, S. S. Lim, A. H. Mokdad, S. E. Vollset, and C. J. L. Murray. 2018. Forecasting life expectancy, years of life lost, and all-cause and cause-specific mortality for 250 causes of death: reference and alternative scenarios for 2016-40 for 195 countries and territories. Lancet 392(10159):2052-2090. https://doi.org/10.1016/S0140-6736(18)31694-5

Gellman, M. D., and J. R. Turner, editors. 2013. Major depressive disorder. Pages 1187-1187. Encyclopedia of behavioral medicine. Springer, New York, New York, USA. https://doi.org/10.1007/978-3-030-39903-0_301110

Grimm, N. B., S. H. Faeth, N. E. Golubiewski, C. L. Redman, J. Wu, X. Bai, and J. M. Briggs. 2008. Global change and the ecology of cities. Science 319(5864):756-760. https://doi.org/10.1126/science.1150195

Grove, M., L. Ogden, S. Pickett, C. Boone, G. Buckley, D. H. Locke, C. Lord, and B. Hall. 2018. The legacy effect: understanding how segregation and environmental injustice unfold over time in Baltimore. Annals of the American Association of Geographers 108(2):524-537. https://doi.org/10.1080/24694452.2017.1365585

Gruebner, O., M. A. Rapp, M. Adli, U. Kluge, S. Galea, and A. Heinz. 2017. Cities and mental health. Deutsches Ärzteblatt International 114(8):121-127. https://doi.org/10.3238/arztebl.2017.0121

Hawe, P., A. Shiell, and T. Riley. 2009. Theorising interventions as events in systems. American Journal of Community Psychology 43(3-4):267-276. https://doi.org/10.1007/s10464-009-9229-9

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

Hitchmough, J. D., and A. M. Bonugli. 1997. Attitudes of residents of a medium-sized town in South West Scotland to street trees. Landscape Research 22(3):327-337. https://doi.org/10.1080/01426399708706518

Hovmand, P. S. 2014. Introduction to community-based system dynamics. Pages 1-16. Community based system dynamics. Springer, New York, New York, USA. https://doi.org/10.1007/978-1-4614-8763-0_1

Kim, D. H. 1994. Systems archetypes. Pegasus Communications, Cambridge, Massachusetts, USA.

Kuo, M. 2015. How might contact with nature promote human health? Promising mechanisms and a possible central pathway. Frontiers in Psychology 6:1093. https://doi.org/10.3389/fpsyg.2015.01093

Landry, S. M., and J. Chakraborty. 2009. Street trees and equity: evaluating the spatial distribution of an urban amenity. Environment and Planning A: Economy and Space 41 (11):2651-2670. https://doi.org/10.1068/a41236

Langellier, B. A., Y. Yang, J. Purtle, K. L. Nelson, I. Stankov, and A. V. Diez Roux. 2019. Complex systems approaches to understand drivers of mental health and inform mental health policy: a systematic review. Administration and Policy in Mental Health and Mental Health Services Research 46(2):128-144. https://doi.org/10.1007/s10488-018-0887-5

Lorenc, T., S. Clayton, D. Neary, M. Whitehead, M. Petticrew, H. Thomson, S. Cummins, A. Sowden, and A. Renton. 2012. Crime, fear of crime, environment, and mental health and well-being: mapping review of theories and causal pathways. Health & Place 18(4):757-765. https://doi.org/10.1016/j.healthplace.2012.04.001

Lorenc, T., M. Petticrew, M. Whitehead, D. Neary, S. Clayton, K. Wright, H. Thomson, S. Cummins, A. Sowden, and A. Renton. 2014. Crime, fear of crime and mental health: synthesis of theory and systematic reviews of interventions and qualitative evidence. Public Health Research 2(2). https://doi.org/10.3310/phr02020

Markevych, I., J. Schoierer, T. Hartig, A. Chudnovsky, P. Hystad, A. M. Dzhambov, S. de Vries, M. Triguero-Mas, M. Brauer, M. J. Nieuwenhuijsen, G. Lupp, E. A. Richardson, T. Astell-Burt, D. Dimitrova, X. Feng, M. Sadeh, M. Standl, J. Heinrich, and E. Fuertes. 2017. Exploring pathways linking greenspace to health: theoretical and methodological guidance. Environmental Research 158:301-317. https://doi.org/10.1016/j.envres.2017.06.028

Marselle, M. R., D. E. Bowler, J. Watzema, D. Eichenberg, T. Kirsten, and A. Bonn. 2020. Urban street tree biodiversity and antidepressant prescriptions. Scientific Reports 10(1):22445. https://doi.org/10.1038/s41598-020-79924-5

McGill, E., V. Er, T. Penney, M. Egan, M. White, P. Meier, M. Whitehead, K. Lock, R. Anderson de Cuevas, R. Smith, N. Savona, H. Rutter, D. Marks, F. de Vocht, S. Cummins, J. Popay, and M. Petticrew. 2021. Evaluation of public health interventions from a complex systems perspective: a research methods review. Social Science & Medicine 272:113697. https://doi.org/10.1016/j.socscimed.2021.113697

McGill, E., D. Marks, V. Er, T. Penney, M. Petticrew, and M. Egan. 2020. Qualitative process evaluation from a complex systems perspective: a systematic review and framework for public health evaluators. PLOS Medicine 17(11):e1003368. https://doi.org/10.1371/journal.pmed.1003368

McPherson, E. G., S. E. Maco, J. R. Simpson, P. J. Peper, Q. Xiao, A. M. VanDerZanden, and N. Bell. 2002. Western Washington and Oregon community tree guide: benefits, costs and strategic planting. International Society of Arboriculture, Pacific Northwest Chapter, Silverton, Oregon, USA.

Meadows, D. H., and D. Wright. 2009. Thinking in systems: a primer. Earthscan, London, UK.

Mullaney, J., T. Lucke, and S. J. Trueman. 2015. A review of benefits and challenges in growing street trees in paved urban environments. Landscape and Urban Planning 134:157-166. https://doi.org/10.1016/j.landurbplan.2014.10.013

Okkels, N., C. B. Kristiansen, P. Munk-Jørgensen, and N. Sartorius. 2018. Urban mental health: challenges and perspectives. Current Opinion in Psychiatry 31(3):258-264. https://doi.org/10.1097/YCO.0000000000000413

Orimoloye, I. R., S. P. Mazinyo, A. M. Kalumba, O. Y. Ekundayo, and W. Nel. 2019. Implications of climate variability and change on urban and human health: a review. Cities 91:213-223. https://doi.org/10.1016/j.cities.2019.01.009

Pauleit, S., N. Jones, G. Garcia-Martin, J. L. Garcia-Valdecantos, L. M. Rivière, L. Vidal-Beaudet, M. Bodson, and T. B. Randrup. 2002. Tree establishment practice in towns and cities - results from a European survey. Urban Forestry & Urban Greening 1 (2):83-96. https://doi.org/10.1078/1618-8667-00009

Pawson, R., T. Greenhalgh, G. Harvey, and K. Walshe. 2004. Realist synthesis: an introduction. ESRC Research Methods Programme Working Paper Series.

Petticrew, M., C. Knai, J. Thomas, E. A. Rehfuess, J. Noyes, A. Gerhardus, J. M. Grimshaw, H. Rutter, and E. McGill. 2019. Implications of a complexity perspective for systematic reviews and guideline development in health decision making. BMJ Global Health 4(Suppl 1):e000899. https://doi.org/10.1136/bmjgh-2018-000899

Rae, R. A., G. Simon, and J. Braden. 2010. Public reactions to new street tree planting. Cities and the Environment 3:21. https://doi.org/10.15365/cate.31102010

Rahman, M. A., J. G. Smith, P. Stringer, and A. R. Ennos. 2011. Effect of rooting conditions on the growth and cooling ability of Pyrus calleryana. Urban Forestry & Urban Greening 10 (3):185-192. https://doi.org/10.1016/j.ufug.2011.05.003

Rifkin, D. I., M. W. Long, and M. J. Perry. 2018. Climate change and sleep: a systematic review of the literature and conceptual framework. Sleep Medicine Reviews 42:3-9. https://doi.org/10.1016/j.smrv.2018.07.007

Roy, S., J. Byrne, and C. Pickering. 2012. A systematic quantitative review of urban tree benefits, costs, and assessment methods across cities in different climatic zones. Urban Forestry & Urban Greening 11(4):351-363. https://doi.org/10.1016/j.ufug.2012.06.006

Rutter, H., N. Savona, K. Glonti, J. Bibby, S. Cummins, D. T. Finegood, F. Greaves, L. Harper, P. Hawe, L. Moore, M. Petticrew, E. Rehfuess, A. Shiell, J. Thomas, and M. White. 2017. The need for a complex systems model of evidence for public health. Lancet 390:10112 https://doi.org/10.1016/S0140-6736(17)31267-9

Salmond, J. A., M. Tadaki, S. Vardoulakis, K. Arbuthnott, A. Coutts, M. Demuzere, K. N. Dirks, C. Heaviside, S. Lim, H. Macintyre, R. N. McInnes, and B. W. Wheeler. 2016. Health and climate related ecosystem services provided by street trees in the urban environment. Environmental Health 15(S1):S36. https://doi.org/10.1186/s12940-016-0103-6

Sangalang, C. C., and C. Vang. 2017. Intergenerational trauma in refugee families: a systematic review. Journal of Immigrant and Minority Health 19(3):745-754. https://doi.org/10.1007/s10903-016-0499-7

Schram, A., A. Ruckert, J. A. VanDuzer, S. Friel, D. Gleeson, A.-M. Thow, D. Stuckler, and R. Labonte. 2017. A conceptual framework for investigating the impacts of international trade and investment agreements on noncommunicable disease risk factors. Health Policy and Planning 33(1):123-136. https://doi.org/10.1093/heapol/czx133

Shashua-Bar, L., D. Pearlmutter, and E. Erell. 2009. The cooling efficiency of urban landscape strategies in a hot dry climate. Landscape and Urban Planning 92(3-4):179-186. https://doi.org/10.1016/j.landurbplan.2009.04.005

Shcheglovitova, M. 2020. Valuing plants in devalued spaces: caring for Baltimore's Street trees. Environment and Planning E: Nature and Space 3(1):228-245. https://doi.org/10.1177/2514848619854375

Skivington, K., L. Matthews, S. A. Simpson, P. Craig, J. Baird, J. M. Blazeby, K. A. Boyd, N. Craig, D. P. French, E. McIntosh, M. Petticrew, J. Rycroft-Malone, M. White, and L. Moore. 2021. A new framework for developing and evaluating complex interventions: update of Medical Research Council guidance. BMJ 374:n2061. https://doi.org/10.1136/bmj.n2061

Sterman, J. 2000. Business dynamics: systems thinking and modeling for a complex world. Irwin/McGraw-Hill, Homewood, Illinois, USA.

Stringer, D. M. 2013. Negative affect. Pages 1303-1304 in M. D. Gellman and J. R. Turner, editors. Encyclopedia of behavioral medicine. Springer, New York, New York, USA. https://doi.org/10.1007/978-3-030-39903-0_606

Taylor, M. S., B. W. Wheeler, M. P. White, T. Economou, and N. J. Osborne. 2015. Research note: urban street tree density and antidepressant prescription rates—a cross-sectional study in London, UK. Landscape and Urban Planning 136:174-179. https://doi.org/10.1016/j.landurbplan.2014.12.005

Trees and Design Action group. 2014. Trees in hard landscapes: a guide for delivery.

Vennix, J. A. M. 1999. Group model-building: tackling messy problems. System Dynamics Review 15(4):379-401. https://doi.org/10.1002/(SICI)1099-1727(199924)15:4%3C379::AID-SDR179%3E3.0.CO;2-E

Vigo, D., G. Thornicroft, and R. Atun. 2016. Estimating the true global burden of mental illness. Lancet Psychiatry 3(2):171-178. https://doi.org/10.1016/S2215-0366(15)00505-2

Vogt, J., and M. Abood. 2020. A transdisciplinary, mixed methods research agenda for evaluating the collective impact approach for tree planting: the CommuniTree initiative in northwest Indiana, U.S. Urban Forestry & Urban Greening 53:126735. https://doi.org/10.1016/j.ufug.2020.126735

Watkins, S. L., S. K. Mincey, J. Vogt, and S. P. Sweeney. 2017. Is planting equitable? An examination of the spatial distribution of nonprofit urban tree-planting programs by canopy cover, income, race, and ethnicity. Environment and Behavior 49(4):452-482. https://doi.org/10.1177/0013916516636423

Watts, N., M. Amann, N. Arnell, S. Ayeb-Karlsson, J. Beagley, K. Belesova, M. Boykoff, P. Byass, W. Cai, D. Campbell-Lendrum, S. Capstick, J. Chambers, S. Coleman, C. Dalin, M. Daly, N. Dasandi, S. Dasgupta, M. Davies, C. D. Napoli, P. Dominguez-Salas, P. Drummond, R. Dubrow, K. L. Ebi, M. Eckelman, P. Ekins, L. E. Escobar, L. Georgeson, S. Golder, D. Grace, H. Graham, P. Haggar, I. Hamilton, S. Hartinger, J. Hess, S.-C. Hsu, N. Hughes, S. J. Mikhaylov, M. P. Jimenez, I. Kelman, H. Kennard, G. Kiesewetter, P. L. Kinney, T. Kjellstrom, D. Kniveton, P. Lampard, B. Lemke, Y. Liu, Z. Liu, M. Lott, R. Lowe, J. Martinez-Urtaza, M. Maslin, L. McAllister, A. McGushin, C. McMichael, J. Milner, M. Moradi-Lakeh, K. Morrissey, S. Munzert, K. A. Murray, T. Neville, M. Nilsson, M. O. Sewe, T. Oreszczyn, M. Otto, F. Owfi, O. Pearman, D. Pencheon, R. Quinn, M. Rabbaniha, E. Robinson, J. Rocklöv, M. Romanello, J. C. Semenza, J. Sherman, L. Shi, M. Springmann, M. Tabatabaei, J. Taylor, J. Triñanes, J. Shumake-Guillemot, B. Vu, P. Wilkinson, M. Winning, P. Gong, H. Montgomery, and A. Costello. 2021. The 2020 report of The Lancet Countdown on health and climate change: responding to converging crises. Lancet 397(10269):129-170. https://doi.org/10.1016/S0140-6736(20)32290-X

Werbin, Z. R., L. Heidari, S. Buckley, P. Brochu, L. J. Butler, C. Connolly, L. H. Bloemendaal, T. D. McCabe, T. K. Miller, and L. R. Hutyra. 2020. A tree-planting decision support tool for urban heat mitigation. PLoS ONE 15(10):e0224959. https://doi.org/10.1371/journal.pone.0224959

Widney, S., B. C. Fischer, and J. Vogt. 2016. Tree mortality undercuts ability of tree-planting programs to provide benefits: results of a three-city study. Forests 7(3):65. https://doi.org/10.3390/f7030065

Wilson, J. Q., and G. L. Kelling. 1982. Broken windows. The Atlantic. March. https://www.theatlantic.com/magazine/archive/1982/03/broken-windows/304465/

Wittenborn, A. K., H. Rahmandad, J. Rick, and N. Hosseinichimeh. 2016. Depression as a systemic syndrome: mapping the feedback loops of major depressive disorder. Psychological Medicine 46(3):551-562. https://doi.org/10.1017/S0033291715002044

Wolf, K. L., S. T. Lam, J. K. McKeen, G. R. A. Richardson, M. van den Bosch, and A. C. Bardekjian. 2020. Urban trees and human health: a scoping review. International Journal of Environmental Research and Public Health 17(12):4371. https://doi.org/10.3390/ijerph17124371

Wolstenholme, E. 2004. Using generic system archetypes to support thinking and modelling. System Dynamics Review 20(4):341-356. https://doi.org/10.1002/sdr.302

World Health Organization. 2018. Mental health: strengthening our response. https://www.who.int/news-room/fact-sheets/detail/mental-health-strengthening-our-response

Appendix 1: Included studies

Alvarsson, J. J., S. Wiens, and M. E. Nilsson. 2010. Stress Recovery during Exposure to Nature Sound and Environmental Noise. International Journal of Environmental Research and Public Health 7(3):1036–1046.

Anderson, C. A. 2001. Heat and Violence. Current Directions in Psychological Science 10(1):33–38.

Anderson, L. M., and H. K. Cordell. 1988. Influence of trees on residential property values in Athens, Georgia (U.S.A.): A survey based on actual sales prices. Landscape and Urban Planning 15(1–2):153–164.

Arnberger, A., B. Allex, R. Eder, M. Ebenberger, A. Wanka, F. Kolland, P. Wallner, and H.-P. Hutter. 2017. Elderly resident's uses of and preferences for urban green spaces during heat periods. Urban Forestry & Urban Greening 21:102–115.

Astell-Burt, T., and X. Feng. 2019. Urban green space, tree canopy, and prevention of heart disease, hypertension, and diabetes: a longitudinal study. The Lancet Planetary Health 3:S16.

Astell-Burt, T., and X. Feng. 2020. Does sleep grow on trees? A longitudinal study to investigate potential prevention of insufficient sleep with different types of urban green space. SSM - Population Health 10:100497.

van den Berg, M. H., J. W. Schoones, and T. P. Vliet Vlieland. 2007. Internet-Based Physical Activity Interventions: A Systematic Review of the Literature. Journal of Medical Internet Research 9(3).

Berland, A., S. A. Shiflett, W. D. Shuster, A. S. Garmestani, H. C. Goddard, D. L. Herrmann, and M. E. Hopton. 2017. The role of trees in urban stormwater management. Landscape and Urban Planning 162:167–177.

Bignal, K. L., M. R. Ashmore, A. D. Headley, K. Stewart, and K. Weigert. 2007. Ecological impacts of air pollution from road transport on local vegetation. Applied Geochemistry 22(6):1265–1271.

Blunt, S. M. 2008. Trees and Pavements—Are They Compatible? Arboricultural Journal 31(2):73–80.

Borst, H. C., H. M. E. Miedema, S. I. de Vries, J. M. A. Graham, and J. E. F. van Dongen. 2008. Relationships between street characteristics and perceived attractiveness for walking reported by elderly people. Journal of Environmental Psychology 28(4):353–361.

Brewin, C. R., B. Andrews, S. Rose, and M. Kirk. 1999. Acute Stress Disorder and Posttraumatic Stress Disorder in Victims of Violent Crime. American Journal of Psychiatry 156(3):360–366.

Burley, B. A. 2018. Green infrastructure and violence: Do new street trees mitigate violent crime? Health & Place 54:43–49.

Cohen-Shacham, E., G. Walters, C. Janzen, and S. Maginnis. 2016a. Nature-based Solutions to address global societal challenges. Page xiii+97pp-xiii+97pp. Gland, Switzerland.

Cohen-Shacham, E., G. Walters, C. Janzen, and S. Maginnis, editors. 2016b. Nature-based solutions to address global societal challenges. IUCN International Union for Conservation of Nature.

Coutts, A. M., J. Beringer, S. Jimi, and N. J. Tapper. 2009. The urban heat island in Melbourne: drivers, spatial and temporal variability, and the vital role of stormwater:8.

Cunningham, B. 2011a. Independent inquiry into management of trees on public land: Final report extract:25.

Cunningham, B. 2011b. Independent inquiry into management of trees on public land: Final report extract:25.

Dadvand, P., M. J. Nieuwenhuijsen, M. Esnaola, J. Forns, and X. Basagaña. 2015. Green spaces and cognitive development in primary schoolchildren 112(26).

Dawes, L. C., A. E. Adams, F. J. Escobedo, and J. R. Soto. 2018. Socioeconomic and ecological perceptions and barriers to urban tree distribution and reforestation programs. Urban Ecosystems 21(4):657–671.

Derkzen, M. L., A. J. A. van Teeffelen, and P. H. Verburg. 2017. Green infrastructure for urban climate adaptation: How do residents' views on climate impacts and green infrastructure shape adaptation preferences? Landscape and Urban Planning 157:106–130.

van Dillen, S. M. E., S. de Vries, P. P. Groenewegen, and P. Spreeuwenberg. 2012. Greenspace in urban neighbourhoods and residents' health: adding quality to quantity. Journal of Epidemiology and Community Health 66(6):e8–e8.

Donovan, G. H., and D. T. Butry. 2010. Trees in the city: Valuing street trees in Portland, Oregon. Landscape and Urban Planning 94(2):77–83.

Donovan, G. H., D. T. Butry, Y. L. Michael, J. P. Prestemon, A. M. Liebhold, D. Gatziolis, and M. Y. Mao. 2013. The Relationship Between Trees and Human Health. American Journal of Preventive Medicine 44(2):139–145.

Donovan, G. H., and J. P. Prestemon. 2012. The Effect of Trees on Crime in Portland, Oregon. Environment and Behavior 44(1):3–30.

Eisenman, T. S., G. Churkina, S. P. Jariwala, P. Kumar, G. S. Lovasi, D. E. Pataki, K. R. Weinberger, and T. H. Whitlow. 2019. Urban trees, air quality, and asthma: An interdisciplinary review. Landscape and Urban Planning 187:47–59.

Ely, M. 2009. Planning for Trees in Urban Environments. Pages 87–98. The University of Adelaide.

Ely, M. 2010. Integrating trees into the design of the city. The University of Adelaide.

Evans, J., S. Hyndman, S. Stewart-Brown, D. Smith, and S. Petersen. 2000. An epidemiological study of the relative importance of damp housing in relation to adult health. Journal of Epidemiology & Community Health 54(9):677–686.

Flannigan, J. 2005a. An Evaluation of Residents' Attitudes to Street Trees in Southwest England. Arboricultural Journal 28(4):219–241.

Flannigan, J. 2005b. An Evaluation of Residents' Attitudes to Street Trees in Southwest England. Arboricultural Journal 28(4):219–241.

Giergiczny, M., and J. Kronenberg. 2014. From Valuation to Governance: Using Choice Experiment to Value Street Trees. AMBIO 43(4):492–501.

Green, D. L., and N. Diaz. 2007. Predictors of Emotional Stress in Crime Victims: Implications for Treatment. Brief Treatment and Crisis Intervention 7(3):194.

Greenblue Urban. 2018. Street Tree Cost Benefit Analysis.

Gulyás, Á., J. Unger, and A. Matzarakis. 2006. Assessment of the microclimatic and human comfort conditions in a complex urban environment: Modelling and measurements. Building and Environment 41(12):1713–1722.

Heimlich, J., T. D. Sydnor, M. Bumgardner, and P. O'Brien. 2008. Attitudes of Residents Toward Street Trees on Four Streets in Toledo, Ohio, U.S. Before Removal of Ash Trees (Fraxinus spp.) from Emerald Ash Borer (Agrilus planipennis):7.

Hewett, P. 2009. Urban Forest: Risk Started the Ball Rolling - So What Will Sustain It? Page 10th National Street Tree Symposium.

Hitchmough, J. D., and A. M. Bonugli. 1997. Attitudes of residents of a medium sized town in South West Scotland to street trees. Landscape Research 22(3):327–337.

Jeon-Slaughter, H., C. A. Claassen, D. A. Khan, P. Mihalakos, K. B. Lee, and E. S. Brown. 2016. Temporal Association Between Nonfatal Self-Directed Violence and Tree and Grass Pollen Counts. The Journal of Clinical Psychiatry 77(9):1160–1167.

Kirkpatrick, J. B., A. Davison, and G. D. Daniels. 2012a. Resident attitudes towards trees influence the planting and removal of different types of trees in eastern Australian cities. Landscape and Urban Planning 107(2):147–158.

Kirkpatrick, J. B., A. Davison, and G. D. Daniels. 2012b. Resident attitudes towards trees influence the planting and removal of different types of trees in eastern Australian cities. Landscape and Urban Planning 107(2):147–158.

Ko, Y. 2018. Trees and vegetation for residential energy conservation: A critical review for evidence-based urban greening in North America. Urban Forestry & Urban Greening 34:318–335.

Kuo, F. E. 2001. Coping with Poverty: Impacts of Environment and Attention in the Inner City. Environment and Behavior 33(1):5–34.

Kuo, F. E., and W. C. Sullivan. 2001a. Environment and Crime in the Inner City: Does Vegetation Reduce Crime? Environment and Behavior 33(3):343–367.

Kuo, F. E., and W. C. Sullivan. 2001b. Environment and Crime in the Inner City: Does Vegetation Reduce Crime? Environment and Behavior 33(3):343–367.

Kuo, F. E., and W. C. Sullivan. 2001c. Aggression and Violence in the Inner City: Effects of Environment via Mental Fatigue. Environment and Behavior 33(4):543–571.

Kuo, M. 2015. How might contact with nature promote human health? Promising mechanisms and a possible central pathway. Frontiers in Psychology 6.

Liddell, C., and C. Guiney. 2015. Living in a cold and damp home: frameworks for understanding impacts on mental well-being. Public Health 129(3):191–199.

Livesley, S. J., E. G. McPherson, and C. Calfapietra. 2016a. The Urban Forest and Ecosystem Services: Impacts on Urban Water, Heat, and Pollution Cycles at the Tree, Street, and City Scale. Journal of Environmental Quality 45(1):119–124.

Livesley, S. J., G. M. McPherson, and C. Calfapietra. 2016b. The Urban Forest and Ecosystem Services: Impacts on Urban Water, Heat, and Pollution Cycles at the Tree, Street, and City Scale. Journal of environmental quality 45(1):119–124.

Lohr, V. I., C. H. Pearson-Mims, J. Tarnai, and D. A. Dillman. 2004. How Urban Residents Rate and Rank the Benefits and Problems Associated with Trees in Cities:8.

Lovasi, G. S., J. W. Quinn, K. M. Neckerman, M. S. Perzanowski, and A. Rundle. 2008a. Children living in areas with more street trees have lower prevalence of asthma. Journal of epidemiology and community health 62(7):647–649.

Lovasi, G. S., J. W. Quinn, K. M. Neckerman, M. S. Perzanowski, and A. Rundle. 2008b. Children living in areas with more street trees have lower prevalence of asthma. Journal of epidemiology and community health 62(7):647–649.

Lu, J. W. T., E. S. Svendsen, L. K. Campbell, J. Greenfeld, J. Braden, K. L. King, and N. Falxa-Raymond. 2010. Biological, Social, and Urban Design Factors Affecting Young Street Tree Mortality in New York City. Cities and the Environment 3:15.

Maas, J., S. M. E. van Dillen, R. A. Verheij, and P. P. Groenewegen. 2009. Social contacts as a possible mechanism behind the relation between green space and health. Health & Place 15(2):586–595.

McDonald, R., T. Kroeger, T. Boucher, W. LongZhu, and R. Salem. 2016. Planting healthy air: a global analysis of the role of urban trees in addressing particulate matter pollution and extreme heat. Planting healthy air: a global analysis of the role of urban trees in addressing particulate matter pollution and extreme heat.

McPherson, E. G., S. E. Maco, J. R. Simpson, P. J. Peper, Q. Xiao, A. M. VanDerZanden, and N. Bell. 2002. Western Washington and Oregon Community Tree Guide: Benefits, Costs and Strategic Planting:84.

McPherson, E. G., and P. P. Peper. 1996. Costs of Street Tree Damage to Infrastructure. Arboricultural Journal 20(2):143–160.

Morgenroth, J., J. Östberg, C. Konijnendijk van den Bosch, A. B. Nielsen, R. Hauer, H. Sjöman, W. Chen, and M. Jansson. 2016. Urban tree diversity—Taking stock and looking ahead. Urban Forestry & Urban Greening 15:1–5.

Narayanan, D. L., R. N. Saladi, and J. L. Fox. 2010. Review: Ultraviolet radiation and skin cancer. International Journal of Dermatology 49(9):978–986.

Pandit, R., M. Polyakov, and R. Sadler. 2012. The importance of tree cover and neighbourhood parks in determining urban property values:16.

Pauleit, S., N. Jones, G. Garcia-Martin, J. L. Garcia-Valdecantos, L. M. Rivière, L. Vidal-Beaudet, M. Bodson, and T. B. Randrup. 2002. Tree establishment practice in towns and cities – Results from a European survey. Urban Forestry & Urban Greening 1(2):83–96.

Plant, L. 2009. Are your Urban Trees in the Climate Change and Sustainability Spotlight?

Rahman, M. A., J. G. Smith, P. Stringer, and A. R. Ennos. 2011. Effect of rooting conditions on the growth and cooling ability of Pyrus calleryana. Urban Forestry & Urban Greening 10(3):185–192.

Reiner, M., C. Niermann, D. Jekauc, and A. Woll. 2013. Long-term health benefits of physical activity – a systematic review of longitudinal studies. BMC Public Health 13(1):813.

Rifkin, D. I., M. W. Long, and M. J. Perry. 2018a. Climate change and sleep: A systematic review of the literature and conceptual framework. Sleep Medicine Reviews 42:3–9.

Rifkin, D. I., M. W. Long, and M. J. Perry. 2018b. Climate change and sleep: A systematic review of the literature and conceptual framework. Sleep Medicine Reviews 42:3–9.

Roetman, P. E. J., and C. B. Daniels. 2008. Including Biodiveristy as a Component of Sustainability as Australian Cities Grow: Why and How?12.

Salmond, J. A., M. Tadaki, S. Vardoulakis, K. Arbuthnott, A. Coutts, M. Demuzere, K. N. Dirks, C. Heaviside, S. Lim, H. Macintyre, R. N. McInnes, and B. W. Wheeler. 2016a. Health and climate related ecosystem services provided by street trees in the urban environment. Environmental Health 15(1):S36.

Salmond, J. A., M. Tadaki, S. Vardoulakis, K. Arbuthnott, A. Coutts, M. Demuzere, K. N. Dirks, C. Heaviside, S. Lim, H. Macintyre, R. N. McInnes, and B. W. Wheeler. 2016b. Health and climate related ecosystem services provided by street trees in the urban environment. Environmental health : a global access science source 15 Suppl 1(Suppl 1):36.

Sander, H., S. Polasky, and R. G. Haight. 2010. The value of urban tree cover: A hedonic property price model in Ramsey and Dakota Counties, Minnesota, USA. Ecological Economics 69(8):1646–1656.

Sansone, R. A., and L. A. Sansone. 2011. Allergic Rhinitis. Innovations in Clinical Neuroscience 8(7):12–17.

Sanusi, R., D. Johnstone, P. May, and S. J. Livesley. 2016. Street Orientation and Side of the Street Greatly Influence the Microclimatic Benefits Street Trees Can Provide in Summer. Journal of Environmental Quality 45(1):167–174.

Sarkar, A., and R. Bardhan. 2019. Optimal interior design for naturally ventilated low-income housing: a design-route for environmental quality and cooling energy saving. Advances in Building Energy Research 0(0):1–33.

Sarkar, C., C. Webster, M. Pryor, D. Tang, S. Melbourne, X. Zhang, and L. Jianzheng. 2015. Exploring associations between urban green, street design and walking: Results from the Greater London boroughs. Landscape and Urban Planning 143:112–125.

Schroeder, H., J. Flannigan, and R. Coles. 2006. Residents' Attitudes Toward Street Trees in the UK and U.S. Communities.

Schroeder, H. W., and W. N. Cannon. 1983. The Esthetic Contribution of Trees to Residential Streets in Ohio Towns:7.

Scott, K. I., J. R. Simpson, and E. G. McPherson. 1999. Effects of Tree Cover on Parking Lot Microclimate and Vehicle Emissions:15.

Shashua-Bar, L., D. Pearlmutter, and E. Erell. 2009. The cooling efficiency of urban landscape strategies in a hot dry climate. Landscape and Urban Planning 92(3–4):179–186.

Silvera Seamans, G. 2013. Mainstreaming the environmental benefits of street trees. Urban Forestry & Urban Greening 12(1):2–11.

Stovin, V. R., A. Jorgensen, and A. Clayden. 2008. Street Trees and Stormwater Management:15.

Sugiyama, T., E. Leslie, B. Giles-Corti, and N. Owen. 2008. Associations of neighbourhood greenness with physical and mental health: do walking, social coherence and local social interaction explain the relationships? Journal of Epidemiology & Community Health 62(5):e9–e9.

Sullivan, W. C., F. E. Kuo, and S. F. Depooter. 2004. The Fruit of Urban Nature: Vital Neighborhood Spaces. Environment and Behavior 36(5):678–700.

Sweeney, K. 2009. Are we there yet? Learning from the Past: Lesson for the Future. Page 10th National Street Tree Symposium.

Sygna, K., G. M. Aasvang, G. Aamodt, B. Oftedal, and N. H. Krog. 2014. Road traffic noise, sleep and mental health. Environmental Research 131:17–24.

Tarran, J. 2009. Improving Canberra's sustainability: Why urban tree canopy and other vegetation matters. Page ACTPLA Bush Capital Workshop.

Taylor, A. F., F. E. Kuo, and W. C. Sullivan. 2002. Views of Nature and Self-Discipline: Evidence from Inner City Children. Journal of Environmental Psychology 22(1–2):49–63.

Taylor, M. S., B. W. Wheeler, M. P. White, T. Economou, and N. J. Osborne. 2015. Research note: Urban street tree density and antidepressant prescription rates—A cross-sectional study in London, UK. Landscape and Urban Planning 136:174–179.

Trees and Design Action group. 2014. Trees in Hard Landscapes: A Guide for Delivery.

Ulrich, R. 1984. View through a window may influence recovery from surgery. Science 224(4647):420–421.

Van den Berg, M. M. H. E., J. Maas, R. Muller, A. Braun, W. Kaandorp, R. Van Lien, M. N. M. Van Poppel, W. Van Mechelen, and A. E. Van den Berg. 2015. Autonomic Nervous System Responses to Viewing Green and Built Settings: Differentiating Between

Sympathetic and Parasympathetic Activity. International Journal of Environmental Research and Public Health 12(12):15860–15874.
de Vries, S., S. M. E. van Dillen, P. P. Groenewegen, and P. Spreeuwenberg. 2013. Streetscape greenery and health: Stress, social cohesion and physical activity as mediators. Social Science & Medicine 94:26–33.
Wittenborn, A. K., H. Rahmandad, J. Rick, and N. Hosseinichimeh. 2016. Depression as a systemic syndrome: mapping the feedback loops of major depressive disorder. Psychological Medicine 46(3):551–562.
Wolf, K. L., S. T. Lam, J. K. McKeen, G. R. A. Richardson, M. van den Bosch, and A. C. Bardekjian. 2020. Urban Trees and Human Health: A Scoping Review. International Journal of Environmental Research and Public Health 17(12):4371.
Xiao, Q., E. G. McPherson, S. L. Ustin, M. E. Grismer, and J. R. Simpson. 2000. Winter rainfall interception by two mature open-grown trees in Davis, California. Hydrological Processes 14(4):763–784.
Yeganeh, A. J., G. Reichard, A. P. McCoy, T. Bulbul, and F. Jazizadeh. 2018. Correlation of ambient air temperature and cognitive performance: A systematic review and meta-analysis. Building and Environment 143:701–716.

Appendix 2

Table 1: Database of hypothesized causal relationships

Cause	P	Effect	D	Evidence	Excerpt	Reference
air pollution	-	average tree health	no	empirical	The oak tree health survey found increased defoliation and insect damage near to the motorway, and the beech tree health survey also found poorer crown condition close to the motorway. Vascular species composition showed a trend towards species adapted to higher N availability close to the motorway, while the moss Polytrichum commune showed a significant decline in frequency with distance from the motorway. The effect of the road was estimated to extend to approximately 100 m at these three sites; this distance was consistent with the measured profile of NO2, which declined to background levels at about 100 m. The results suggest that emissions of air pollutants can have significant ecological impacts on sensitive sites within 100 m of major roads.	Bignal et al., 2007
air pollution	-	cognitive performance	no	empirical	Our study showed a beneficial association between exposure to green space and cognitive development among schoolchildren that was partly mediated by reduction in exposure to air pollution. […] Adding a traffic-related air pollutant (elemental carbon) to models explained 20–65% of our estimated associations between school greenness and 12-mo cognitive development.	Dadvand et al., 2015
air pollution	-	physical health	no	empirical	Controlling for potential confounders, an increase in tree density of 1 standard deviation (SD, 343 trees/km2) was associated with a lower prevalence of asthma (RR, 0.71 per SD of tree density; 95% CI, 0.64 to 0.79), but not with hospitalisations for asthma	Lovasi et al., 2008

					(RR, 0.89 per SD of tree density; 95% CI, 0.75 to 1.06).	
allergy	-	cognitive performance	no	review	Through a review of the relevant articles in the PubMed and PsycINFO databases, the authors found that the majority of studies (9 of 11 studies on anxiety syndromes, 10 of 12 studies on depressive syndromes) indicate associations between allergies and anxiety/mood syndromes, despite a number of methodological variances. In addition, there appear to be a number of potential variables that mediate the relationship between allergies and these two psychiatric phenomena (e.g., allergies may heighten risk for these syndromes by triggering the immune system and cytokines; allergies may impair sleep through nasal obstruction and secondarily exacerbate psychiatric symptoms; and allergies may negatively affect cognitive functioning and contribute to psychiatric disturbance) as well as a possible shared genetic risk.	Sansone and Sansone, 2011
allergy	+	negative affect, interpretation and processing	no	review	Through a review of the relevant articles in the PubMed and PsycINFO databases, the authors found that the majority of studies (9 of 11 studies on anxiety syndromes, 10 of 12 studies on depressive syndromes) indicate associations between allergies and anxiety/mood syndromes, despite a number of methodological variances. In addition, there appear to be a number of potential variables that mediate the relationship between allergies and these two psychiatric phenomena (e.g., allergies may heighten risk for these syndromes by triggering the immune system and cytokines; allergies may impair sleep through nasal obstruction and secondarily exacerbate psychiatric symptoms; and allergies may negatively	Sansone and Sansone, 2011

					affect cognitive functioning and contribute to psychiatric disturbance) as well as a possible shared genetic risk.	
allergy	+	sleep problem	no	review	Through a review of the relevant articles in the PubMed and PsycINFO databases, the authors found that the majority of studies (9 of 11 studies on anxiety syndromes, 10 of 12 studies on depressive syndromes) indicate associations between allergies and anxiety/mood syndromes, despite a number of methodological variances. In addition, there appear to be a number of potential variables that mediate the relationship between allergies and these two psychiatric phenomena (e.g., allergies may heighten risk for these syndromes by triggering the immune system and cytokines; allergies may impair sleep through nasal obstruction and secondarily exacerbate psychiatric symptoms; and allergies may negatively affect cognitive functioning and contribute to psychiatric disturbance) as well as a possible shared genetic risk.	Sansone and Sansone, 2011
appropriate tree planting and maintenance activities	+	average tree health	ye s	expert claim	Water restrictions have impacted on mature trees as well as tree establishment practices, seen partly as a consequence of past inappropriate (but unforeseen) species selection.	Ely, 2010
				expert claim	ETSA pruning practices are a major concern, especially in bushfire prone areas. 'ETSA are a problem and they have always been a problem. Their disregard of correct pruning techniques, hiding behind the claim they must provide power to customers, at the expense of street trees, is false and irresponsible.' W5 [...] Water restrictions have impacted on mature trees as well as tree establishment practices, seen	Ely, 2009

					partly as a consequence of past inappropriate (but unforeseen) species selection.	
				expert claim	Staffing issues include staffing levels (especially for establishment and maintenance), staff skills and knowledge, and the adherence to appropriate standards and specifications.	Ely, 2009
				expert claim	The extensive use of de-icing salt is widespread, except in the Mediterranean area, and this is a well-known cause of serious damage to urban trees (e.g. Brod 1990; Dobson 1991). In some cities special protective measures were taken. These included the use of kerbstones and protective walls around trees (Austria, Denmark and France), the use of straw mats (Denmark), increasing the planting distances from roads (Austria, Netherlands and Denmark) or drainage (Norway). The use of de-icing salt was prohibited on pedestrian walkways in cities in Austria and Germany, and efforts were made to reduce the salt application by precision dosage. For France, summer pruning, while the trees are in leaf, was reported as a means of removing salt from the tree. No data was obtained on the effectiveness of these measures.	Pauleit et al., 2002
				expert claim	Sound tree management practices begin with the selection of appropriate species that fulfil the objective(s) for the tree to be planted (e.g. aesthetic, biological or functional requirements), while minimising any negatives that may be associated with that species. It is imperative that species selection takes into account all of the biological and	Cunningham, 2011

					environmental factors that will affect the tree's life_time performance. New plantings should also consider [...tree] age diversity (to avoid the development of aged cohorts that incur high management costs over a short period of time).	
appropriate tree planting and maintenance activities	+	residents' perception of tree benefits	ye s	case study	As the community understands that Council will undertake regular maintenance, the complaints regarding trees have dropped significantly […] In relation to tree management, the City went from having no tree management team and old policies, to a team of six staff, each of whom holds a Diploma of Arboriculture (AQF 5). This led to the development and adoption of numerous policies and management plans for our 19th century parks, and saw over 6,000 advanced street trees planted since 2004. The provision of tree maintenance services was also reviewed and high quality specifications were developed to ensure the City's trees are managed in a programmed way and to best practice principles. This led to the City's street trees, and half of the park trees, being maintained by external service providers (ie. contracted).	Sweeney, 2009
appropriate tree planting and maintenance activities	+	tree species diversity	no	expert claim	New plantings should also consider the species diversity (to lower the incidence of insect and disease outbreaks),	Cunningham , 2011
				expert claim	Often only a few species are planted and this may give cause for concern, since species diversity is considered an important factor in increasing the resilience of the urban tree population to abiotic and biotic stresses.	Pauleit et al., 2002
appropriate water availability	+	average tree health	no	expert claim	Water availability is also an issue, in terms of the impacts of water restrictions, drought and climate change.	Ely, 2009

					'I’ve found the biggest strain with the tree network, over the last 8 years, has been the climatic conditions. It’s had a hell of an impact on streetscapes.' W6 Water restrictions have impacted on mature trees as well as tree establishment practices, seen partly as a consequence of past inappropriate (but unforeseen) species selection. A particular concern for street trees has been the loss of a supplementary water source from suburban front gardens. 'People used to water nature strips, and the grass areas their side of the fence. I think that moisture in a lot of instances got to the trees. Well that’s been excluded from the equation and the trees are suffering.' W6	
appropriate water availability	+	evapotranspiration	no	empirical	In contrast to previous studies, evapotranspiration rates and surface temperatures are not simply aligned with vegetation cover but rather water availability. Therefore, increased vegetation cover to mitigate the UHI must be accompanied by water retention strategies in order enhance the effectiveness of vegetation. [...] When comparing the three urban sites, results showed that there was not a significant response in rates of evapotranspiration to changes in vegetation cover or impervious surface area. No matter whether it was a built up site, or a more open and vegetated site – rates of evapotranspiration were low across the entire urban landscape. Because the pervious surface areas (particularly the grassed areas) were so dry, they effectively function in a similar manner to impervious surface areas – because the	Coutts et al., 2009

					surface is hard and sheds water quickly and there is little sustained infiltration.	
assessed value	+	municipal resources	no	theoretical	If this increase is also reflected in an increase in a house's assessed value, then trees may increase property tax revenues.	Donovan and Butry, 2010
				empirical	This increase in property value results in an estimated increase of $100 000 (1978 dollars) in the city's property tax revenues.	Anderson and Cordell, 1988
attractiveness of neighborhood	+	implied surveillance	no	theoretical	Well-maintained vegetation outside a home serves as one of the cues to care (Nassauer, 1988), suggesting that the inhabitants actively care about their home territory and potentially implying that an intruder would be noticed and confronted.	Kuo and Sullivan, 2001
				theoretical	For example, the broken windows theory suggests that criminals are attracted to poorly maintained neighborhoods, because evidence of neglect—broken windows, for example—provides visual cues that an area may not be subject to effective law enforcement (Wilson & Kelling, 1982). Therefore, if trees help a neighborhood appear well maintained, they may deter crime. (Although several small-scale experiments support the broken window theory [Braga & Bond, 2008; Keizer, Lindenberg, & Steg, 2008], its use to explain larger changes in crime so far remains controversial.)	Donovan and Prestemon, 2012
attractiveness of neighborhood	+	number of people outside	no	empirical	For adults, the difference is significant; there were on average 125% more adults using green spaces than barren spaces. Green cover is also related to the use of outdoor spaces for both genders: Green spaces contain on average 82% more males and 100% more females than barren spaces.	Sullivan et al, 2004
attractiveness of neighborhood	+	walkability	no	empirical	'Walkability' is a frequently employed index of the quality of the neighbourhood, and is determined by	Borst et al., 2008

					factors such as residential density, land-mix-use, street connectivity, aesthetics, and safety. […] Overall, the results suggest that three main aspects affect perceived attractiveness of streets for walking, namely tidiness of the street, its scenic value and the presence of activity or other people along the street.	
				empirical	Logistic regression models reported a significant association of odds of walking with density of street trees	Sarkar et al., 2015
average tree health	+	evapotranspiration	no	empirical	The enhanced growth and physiological performance of trees grown in Amsterdam soil meant they provided peak evapotranspirational cooling of up to 7 kW, 5 times higher than those grown in pavements.	Rahman et al., 2011
average tree health	-	number of trees dying annually	no	assumption		
average tree health	+	tree canopy	no	assumption		
biodiversity	+	physical health	no	review	Environmental biodiversity has been proposed to contribute to human commensal microbiota — the “good bacteria” living on or in the human body (von Hertzen et al 2011; Rook, 2013). There is some evidence consistent with this proposal: the more forest or agricultural land cover near a child’s home, the more proteobacteria on their skin and the more diverse their gammaproteobacteria (Hanski et al 2012; Ruokolainen et al 2014 has similar findings but does not control for socioeconomic status). Note that these findings did not hold for the diversity of vegetation in a child’s yard, nor for other bacterial classes on the skin (Hanski et al 2012). Commensal microbiota are increasingly understood to play a role in the immune system’s ability to tolerate rather than attack non-threats. Consistent with this, the abundance	Kuo, 2015

					of one particular commensal microorganism on the skin was correlated with levels of an anti-inflammatory cytokine playing a key role in immunologic tolerance (IL-10); this finding obtained in healthy individuals and not in atopic ones (Hanski et al 2012).	
cars	+	air pollution	no	theoretical	If shady pathways helped to reduce the number of kilometres of private car travel by just 1/100thannually, the greenhouse gas emissions avoided is estimated to be around an additional 25% of what is sequestered directly by the trees themselves.	Plant, 2009
climate change	+	perception of trees as an investment	no	case study	In addition, the growing awareness and attitudes across Council about the importance of trees – from the roadway and footpath crews, through to the planners, has steadily increased and improved. This improvement has come from both the 'top down', through the Lord Mayor and Councillors, and the CEO, and also from the 'bottom up' as more individuals are aware of and understand climate change.	Sweeney, 2009
community cohesion	+	community tree stewardship	no	empirical	Data were collected about neighborhood sociability to ascertain whether the tree is incorporated into active street life. For example, benches are built into tree pits, seating is arranged under trees' canopies, or play equipment is often proximate to the tree. At the neighborhood level, signs of sociability indicate more ―eyes upon the street‖ (Jacobs 1961) or the orientation of urban space to enhance community awareness and engagement. This sociability can influence tree survival via multiple pathways, such as through prevention of tree vandalism. [...] In terms of sociability, trees with adjacent seating or an adjacent	Lu et al., 2010

					front yard were all more likely to survive in the urban environment (Table 7).	
community cohesion	+	interpersonal relationship quality	no	empirical	With regard to the importance of social cohesion as a mediator, we come to the same positive conclusion as Sugiyama et al. (2008). Also Maas et al. (2009) point in this direction: in their study loneliness and perceived shortage of social support completely mediated the effect of the amount of greenspace on mental health. This clearly emerging role of social cohesion is remarkable, since it is the least studied of the three mechanisms thus far. It is also not uncontested: Fan et al. (2011) concluded that social support is negatively influenced by the neighbourhood vegetation level.	de Vries et al., 2013
				review	Enhanced social ties appear to be a major contributor to nature’s effects on health. A voluminous literature attests to the importance of social ties for both mental and physical health (for review see Cohen, 2004; Holt-Lunstad et al 2010; Cacioppo & Cacioppo, 2014). Moreover, findings from three studies point to a large role for social integration in the relationship between residential greenness and health. Each of these examined the relationships among residential greenness, social integration, and self-reported health in a large population, and employed statistical mediation testing (Baron & Kenny, 1986). Social integration substantially contributes to the relationship between greenness and perceived mental health (Sugiyama et al 2008; Maas, Van Dillen, et al 2009; de Vries et al 2013), perceived physical health (Sugiyama et al 2008); perceived general health (Maas, Van Dillen, et al 2009; de Vries et al 2013),	Kuo, 2015

					and (fewer) health complaints (Maas, Van Dillen, et al 2009; de Vries et al 2013). No studies as of yet have examined whether these relationships hold for objective measures of health, such as mortality.	
community tree stewardship	+	average tree health	no	empirical	A stewardship index was constructed from factors that directly affect the area in and around the tree pit, including: presence of signage, plantings in pits, mulch, and evidence of weeding. This stewardship index is significantly correlated with tree survival. Planting in the tree pit was the most often observed stewardship behavior (1,039 trees), followed by mulch (962 trees), weeding (317 trees), and signage (232 trees). Evidence of active, direct tree stewardship is a positive indicator or predictor of street tree survival. [...] The presence/absence of tree guards can also be considered as a sociability/stewardship factor, not just a physical design variable. This is because while the mechanism for reduced mortality for street trees with tree guards are physical (by preventing soil compaction or inadvertent contact to the tree by cars), tree guards are typically installed privately and not by NYC Parks, and therefore also represents an act of stewardship. This may vary in other urban areas.	Lu et al., 2010
coordination between organizations	+	appropriate tree planting and maintenance activities	no	theoretical	In order for improved coordination of tree planting and management for stormwater control to occur, communication and information sharing will have to be fostered between formal and informal organizations involved in street tree management	Berland et al., 2017
				expert claim	Professional conflict between arboriculturists and highway engineers is common, not least because the two professions use different terms and measures for many parameters affecting the soil, pavings and tree	Blunt, 2008

					roots. The result is usually the separation of the space below the surface into a zone where engineering design parameters must be achieved regardless of the tree, and a (much smaller) zone in which the arboriculturist is allowed to specify his/her preferred conditions. As a result the choice of species is restricted to trees of small stature and considerable drought tolerance.	
costs	-	municipal resources	no	assumption		
crime	-	crime elsewhere	no	theoretical	by increasing informal surveillance of some outdoor spaces without reducing the actual impetus for burglary and other premeditated crimes, vegetation might serve to simply shift such crimes to more vulnerable targets.	Kuo and Sullivan, 2001
crime	+	stress stimuli	no	empirical	A sample of 175 crime victims—86 violent and 89 nonviolent crime victims—were interviewed. Emotional stress, coping strategy, social support, and individual characteristics were assessed. Multiple regression analyses revealed that the model including individual characteristics, coping strategies, social support, and well-being accounted for more than 74% of the variance. However, only gender, type of crime experienced, coping strategy, and social support significantly predicted emotional stress among crime victims.	Green and Diaz, 2007
				empirical	METHOD: A mixed-sex group of 157 victims of violent assaults were interviewed within 1 month of the crime. At 6-month follow-up 88% were reinterviewed by telephone and completed further assessments generating estimates of the prevalence of PTSD. RESULTS: The rate of acute stress disorder was 19%, and the rate of subsequent PTSD was 20%.	Brewin et al., 1999

					Symptom clusters based on the DSM-IV criteria for acute stress disorder were moderately strongly interrelated.	
deposition on leaves	-	air pollution	no	review	Focusing on PM, an early review summarizing the potential magnitude of air pollution reduction via urban vegetation canopies found that average published deposition values (vd in units of cm s−1) corresponded to an estimated 1% reduction of PM10 across urban areas (Litschke & Kuttler, 2008).	Eisenman et al., 2019
				review	A number of studies43-49 measure the fraction of PM removed by street trees (Table 23), rather than using a decay coefficients approach. In this study, we estimate PM10 removal by street trees using the findings from the five experimental studies that analyze street tree PM10 capture efficiency (i.e., percent difference in PM10 in air upwind and downwind, respectively, of the trees). [...] PM is removed by plants through a process known as dry deposition. Dry deposition is when particles in the atmosphere deposit themselves on a surface, decreasing the atmospheric concentration of PM.36 Much of the fine fraction (PM2.5) becomes permanently incorporated into leaf wax or cuticle, while a portion of the coarse fraction is resuspended as a function of wind speed.37, 38 The remainder of the coarse fraction is eventually washed off to the ground by precipitation.39-42 It is quite clear from the scientific literature that dry deposition of PM occurs, but studies differ on how much PM tree canopies remove. One key parameter controlling how much PM is removed is the concentration of the pollutant: At higher atmospheric concentrations of PM, the rate of dry deposition or absorption is greater.	McDonald et al., 2016

					Another is the leaf area: More leaf area offers more surface area on which dry deposition or absorption can take place. Finally, the amount of mixing of the atmosphere matters as well, with better mixing associated with more canopy removal of PM.	
dispersal around heat	-	temperature	no	review	At night, although the presence of trees may reduce local-scale heat storage and hence release at night, street trees trap radiation within the canyon and reduce ventilation, preventing the dissipation of sensible heat that has built up during the day. Therefore, while an extensive tree canopy cover may be beneficial during the day, there is a risk of restricted nocturnal longwave cooling leading to slightly higher and more uncomfortable indoor temperatures during the night [38]. It should also be noted that trees change aerodynamic resistance to heat diffusion, and may limit the penetration of breezes and cooling of buildings through open windows at night during summer.	Salmond et al., 2016
dispersion around sources of pollutants	-	air pollution	no	review	At the scale of a busy arterial road, this review noted that plants can modify air flow (i.e., dispersion), thus increasing PM concentrations near emission sources such as roads.	Eisenman et al., 2019
economic status	-	tree vandalism	no	empirical	The most frequently ranked reason for not wanting trees was that they would be destroyed by vandals, wasting council tax payers' money for no benefit. What seems to be an extremely negative perception of the inevitably of vandalism is, however, perhaps a realistic one as it was ranked most frequently in the least affluent street, where there was considerable evidence of damage to public and private property.	Hitchmough and Bonugli, 1997
evapotranspiration	-	temperature	no	review	Understanding the role of evapotranspiration from trees on the urban heat balance is also central to	Livesley et al., 2016

					understanding the potential of urban forest strategies to mitigate heat island effects. Through the development of a sophisticated climatic and physiological model, Ballinas and Barradas (2016) reveal that individual trees can provide profound cooling benefits from daily evapotranspiration. The four species studied ranged in average optimal water use from 3.64 to 4.35 L d−1. Their model predicts that evapotranspiration can reduce urban air temperature by 1°C in Mexico City. However, the number of trees needed to achieve a 1°C reduction in daytime air temperature depends on the tree species, as 63 mature Eucalyptus camaldulensis trees per hectare are required to produce the same effect as 24 Liquidambar styraciflua trees.	
heat stress	+	dysfunctional behavior	no	review	High temperatures can cause heat exhaustion, heat-related aggression and violence, and respiratory distress due to heat-related smog formation (Anderson, 2001; Akbari, 2002; Tawatsupa et al., 2012).	Kuo, 2015
				review	Hot temperatures increase aggression by directly increasing feelings of hostility and indirectly increasing aggressive thoughts. Results show that global warming trends may well increase violent-crime rates.	Anderson, 2001
heat stress	-	physical health	no	review	Overall, trees were found to help reduce the risks of heat-related morbidity and mortality and improve thermal comfort in outdoor spaces. [..] There is strong evidence that trees reduce air and surface temperatures [91], but relatively few studies have explored the associated consequences for people's health. We found a total of 17 studies investigating the association between urban trees and excess heat	Wolf et al., 2020

					and thermal comfort. Within this subset, three studies focused on the relationship between trees and heat-related morbidity and mortality using longitudinal/cohort or modelling study designs. These studies found that: trees represent a risk-mitigating factor for heatstroke [92]; tree canopy cover was negatively correlated with heat-related ambulance calls during extreme heat events [93]; and increased vegetative cover was found to help offset projected increases in heat-related mortality for heat wave conditions in 2050 by 40 to 99% across three U.S. metropolitan regions [94]. Across this small group of studies, increased tree and vegetative cover were found to be beneficial in reducing the negative health effects of extreme heat.	
implied surveillance	-	crime	no	theoretical	For example, the broken windows theory suggests that criminals are attracted to poorly maintained neighborhoods, because evidence of neglect—broken windows, for example—provides visual cues that an area may not be subject to effective law enforcement (Wilson & Kelling, 1982). Therefore, if trees help a neighborhood appear well maintained, they may deter crime. (Although several small-scale experiments support the broken window theory [Braga & Bond, 2008; Keizer, Lindenberg, & Steg, 2008], its use to explain larger changes in crime so far remains controversial.)	Donovan and Prestemon, 2012
mental fatigue	+	dysfunctional behaviour	no	empirical	Levels of aggression were compared for 145 urban public housing residents randomly assigned to buildings with varying levels of nearby nature (trees and grass). Attentional functioning was assessed as an index of mental fatigue. Residents living in relatively barren buildings reported more aggression and	Kuo and Sullivan, 2001

					violence than did their counterparts in greener buildings. Moreover, levels of mental fatigue were higher in barren buildings, and aggression accompanied mental fatigue. Tests for the proposed mechanism and for alternative mechanisms indicated that the relationship between nearby nature and aggression was fully mediated through attentional functioning.	
				theoretical	S.Kaplan (1987) suggested that one of the costs of mental fatigue may be a heightened propensity for “outbursts of anger and potentially . . . violence” (p. 57), and three proposed symptoms of mental fatigue—irritability, inattentiveness, and decreased control over impulses—are each well-established psychological precursors to violence. Irritability is linked with aggression in numerous studies (e.g., Caprara & Renzi, 1981; Coccaro, Bergeman, Kavoussi, & Seroczynski, 1997; Kant, Smith-Seemiller, & Zeiler, 1998; Kavoussi & Coccaro, 1998; Stanford, Greve, & Dickens, 1995). Inattentiveness has been closely tied to aggression in both children (Stewart, 1985) andadolescents (Scholte, van Aken, & van Leishout, 1997). And, impulsivity is associated with aggression and violence in a variety of populations (for reviews, see Brady, Myrick & McElroy, 1998; Markovitz, 1995; Tuinier, Verhoeven, & Van Praag, 1996).	Kuo and Sullivan, 2001
mental fatigue	+	violent crime	no	theoretical	S.Kaplan (1987) suggested that one of the costs of mental fatigue may be a heightened propensity for “outbursts of anger and potentially . . . violence” (p. 57), and three proposed symptoms of mental fatigue—irritability, inattentiveness, and decreased control over impulses—are each well-established	Kuo and Sullivan, 2001

					psychological precursors to violence. Irritability is linked with aggression in numerous studies (e.g., Caprara & Renzi, 1981; Coccaro, Bergeman, Kavoussi, & Seroczynski, 1997; Kant, Smith-Seemiller, & Zeiler, 1998; Kavoussi & Coccaro, 1998; Stanford, Greve, & Dickens, 1995). Inattentiveness has been closely tied to aggression in both children (Stewart, 1985) andadolescents (Scholte, van Aken, & van Leishout, 1997). And, impulsivity is associated with aggression and violence in a variety of populations (for reviews, see Brady, Myrick & McElroy, 1998; Markovitz, 1995; Tuinier, Verhoeven, & Van Praag, 1996).	
mould and dampness (in winter)	+	negative affect, interpretation and processing	no	review	Living in cold and damp housing contributes to a variety of different mental health stressors, including persistent worry about debt and affordability, thermal discomfort, and worry about the consequences of cold and damp for health.	Liddell and Guiney, 2015
municipal resources	+	municipal resources for trees	no	case study	In Washington and Oregon, dwindling budgets are forcing an increasing number of cities to shift the costs of sidewalk repair to residents. This shift especially impacts residents in older areas, where large trees have outgrown small sites and infrastructure has deteriorated.	McPherson et al., 2002
municipal resources for trees	+	appropriate tree planting and maintenance activities	no	case study	In Washington and Oregon, dwindling budgets are forcing an increasing number of cities to shift the costs of sidewalk repair to residents. This shift especially impacts residents in older areas, where large trees have outgrown small sites and infrastructure has deteriorated.	McPherson et al., 2002
municipal resources for trees	+	number of trees planted annually	no	assumption		

noise	+	perceived stress	no	review	Plants absorb more high frequency noise than low frequency, which is advantageous to humans since higher frequencies are most distressing to people (Miller 1997).	McPherson et al., 2002
noise	+	sleep problem	no	empirical	The results suggest that road traffic noise may be associated with poorer mental health among subjects with poor sleep. Individuals with poor sleep quality may be more vulnerable to effects of road traffic noise on mental health than individuals with better sleep quality.	Sygna et al., 2014
number of people outside	+	community cohesion	no	empirical	The study confirmed relationships between quantity and quality of streetscape greenery on one hand and stress and social cohesion on the other hand.	de Vries et al., 2013
				review	A large body of studies ranging from experimental to large-scale epidemiological has tied greener settings to social variables, including but not limited to: stronger pro-social aspirations and increased generosity (Weinstein et al 2009), greater shared use of common space and social interaction (Coley et al 1997; Faber Taylor et al 1998; Brunson et al 2001; Sullivan et al 2004), greater social safety (Maas et al 2009), greater mutual trust among neighbors and willingness to help one another (Cohen et al 2008), and greater social integration, social ties, and sense of community (Kuo et al 1998; Kweon et al 1998; Van den Berg et al 2010; Francis et al 2012; de Vries et al 2013; although c.f. mixed findings for different measures of green in Fan et al 2011).	Kuo, 2015
				empirical	We measured social contacts and health in 10,089 residents of the Netherlands and calculated the percentage of green within 1 and a 3 km radius around the postal code coordinates for each individual's address. After adjustment for socio-economic and	Maas et al., 2009

					demographic characteristics, less green space in people's living environment coincided with feelings of loneliness and with perceived shortage of social support. Loneliness and perceived shortage of social support partly mediated the relation between green space and health.	
number of people outside	+	surveillance	no	theoretica l	It may be that trees encourage people to spend more time in public spaces, which increases the probability that criminals are observed.	Donovan and Prestemon, 2012
number of trees dying annually	+	costs	no	case study	In our survey, Western Washington and Oregon cities are recycling most if not all of their green waste from urban trees as mulch, compost, and firewood. In many cases, the net costs of waste wood disposal are less than 1% of total tree care costs as cities and contractors strive to break even (hauling and recycling costs are nearly offset by revenues from purchases of mulch, milled lumber, and firewood). Hauling waste wood and recycling is the primary cost. The city of Longview, WA salvages 85% of its wood waste at a break-even point, and recycles the remaining 15% at a cost of $12/ton ($13/tonne), a substantial savings over the typical landfilling fee of $28/ton ($31/tonne). Sixty-five percent of the salvaged wood is turned into mulch, 30% into firewood, and 5% into milled lumber.	McPherson et al., 2002
number of trees dying annually	-	street tree stock	no	assumption		
number of trees planted annually	+	street tree stock	no	assumption		
perception of trees as an investment	+	appropriate tree planting and	no	case study	The following is illustrative: "Whose *%$#&^* idea was it to make trees assets?" This came from a road maintenance coordinator confronted with the	Hewett, 2009

		maintenance activities			responsibility to consult with the trees coordinator before resurfacing a Council car park where trees had dislodged 'his' kerbs. Herein is evidence of the importance of public trees being part of the assets portfolio.	
perception of trees as an investment	+	municipal resources for trees	no	theoretical	Infrastructure traditionally refers to built assets like roads, bridges, and stormwater constructions such as drains and culverts. It has not included natural resources such as trees, creeks and wetlands. Since the natural resources managed by local government are in the main not defined or managed as assets, then many councils will find it extremely difficult to secure the finance and resources needed to maintain, let alone 'renew', their green infrastructure. [...] Is Asset Management the best way for street trees? The answer is unequivocally 'yes'.	Hewett, 2009
				case study	The legwork that they (CUFR) have done to actually quantify to an economic basis is absolutely critical to all of this so we can actually boil it all down and say: "Trees give back two bucks for every one buck spent. After all of everybody's salaries are paid for all of this $2 M budget is done, trees give back twice [the benefit And that can only be verified by virtue of the urban forest research station. What they have done is absolutely probably the biggest paradigm shift, the biggest shift, leapfrog in urban forestry (PA3 personal interview, 2009).	Silvera Seamans, 2013
				case study	By a happy coincidence, the results were available in the important moment of discussion on a new city development strategy, the first version of which neglected environmental issues. Thus, these results gained publicity and complemented a discussion which helped to revise the strategy to better reflect the	Giergiczny and Kronenberg, 2014

					preferences of Lodz inhabitants. Indeed, the uptake of our results in Lodz confirms that the use of the concept of ecosystem services contributes to better understanding of the benefits of urban nature and reflects a general tendency to refer to the value of urban ecosystem services in various planning documents (Hubacek and Kronenberg 2013)	
pests	-	physical health	no	empirical	A limited number of tree pests can also represent a threat to human health. Of particular concern is the oak processionary moth (OPM – Thaumetopoea processionea). The caterpillars of oak processionary moths have thousands of tiny hairs containing a very irritating substance. The moth is a native of southern and central Europe, where predators and environmental factors usually minimise its impact. However, aided by the movement of plants, its range has expanded northwards over the past 20 years	Trees in Hard Landscapes, 2014
physical activity	+	physical health	no	review	The results of these studies show that physical activity appears to have a positive long-term influence on all selected diseases.	Reiner et al., 2013
pollen	+	allergy	no	review	We found 40 studies that evaluated tree pollen and VOCs emitted by trees, and their potential adverse effects on health such as the exacerbation of allergy, asthma, and rhinitis symptoms, and related behavior such as suicidal self-directed violence [53]. A range of study designs were employed with cross-sectional approaches being the most prevalent, followed by time series, longitudinal/cohort, modelling, and experimental studies (Table 2). Most studies found that higher pollen concentrations are associated with allergy exacerbation, which may lead to increased anti-allergy drug consumption [54–57] or hospital	Wolf et al., 2020

					visits/admissions [58–62]. However, several studies noted that adverse health outcomes are not predicted solely by pollen concentrations as biophysical factors such as temperature, humidity, and ambient concentrations of air pollutants can produce synergies (e.g., [57,62–66]), and there is variable response associated with a person's age [67]	
pollen	+	physical health	no	empirical	There were statistically significant and positive temporal associations between tree pollen counts and the number of nonfatal SDV events among women (P = .04)	Jeon-Slaughter et al., 2016
				review	We found 40 studies that evaluated tree pollen and VOCs emitted by trees, and their potential adverse effects on health such as the exacerbation of allergy, asthma, and rhinitis symptoms, and related behavior such as suicidal self-directed violence [53].	Wolf et al., 2020
property value	+	assessed value	no	theoretical	If this increase is also reflected in an increase in a house's assessed value, then trees may increase property tax revenues.	Donovan and Butry, 2010
rainfall interception	+	water quality	no	review		Stovin, et al., 2008
residents' perception of tree benefits	+	number of trees planted annually	no	empirical	The most widely cited reason for planting trees was for their beauty (84%). Other reasons cited by more than 60% of the respondents were to improve the appearance of the garden (83%), to attract birds and animals (82%), to enhance privacy (75%), because of the beauty of the flowers (66%), to attract native wildlife (62%) and to improve the appearance of the house (60%).	Kirkpatrick et al., 2012
residents' perception of tree benefits	+	perception of trees as an investment	no	theoretical	Furthermore, many people themselves are yet to recognise the diverse benefits provided by trees and other plants and advocate more strongly for their right to live in green cities and towns	Tarran, 2009

				empirical	Respondents had a notion of and concerns about climate impacts, but did not necessarily acknowledgethat GI may help tackle these issues. Yet, when residents were informed about the adaptation capacity of different GI measures, their preferences shifted towards the most effective options. [...] The informational intervention resulted in a shift to more effective GI measures (Table 5). At home level, respondents who received climate adaptation information favoured the green roof option over a garden or green wall, and at street level the information led to more people choosing trees over shrubs or grass.	Derkzen et al., 2017
				review	Gilbert's (1996) analysis of tree survival rates on selected development sites in Sheffield over two decades sites observed that, 'A proportion of tree losses (3-35 per cent) were a delayed result of damage incurred during construction but the majority were removed as a result of complaints, or direct action, by the residents ...	Flannigan, 2005
rooting volume	+	average tree health	no	empirical	Street tree planting systems which are to produce healthy trees of mature stature must provide a rooting zone which supplies enough water to meet the needs of the trees during a year of drought stress. Depending on the stature of tree involved, that could mean 100m3, 200m3 or more.	Blunt, 2008
shade	-	temperature	no	empirical	Compared to a non-vegetated exposed courtyard, which on average reached a maximum air temperature of 34 ◦C in mid-afternoon, a similar courtyard treated with shade trees and grass yielded a daytime temperature depression of up to 2.5 K, while shading the courtyard with a fabric shading mesh, counter-intuitively, caused a relative increase of nearly 1 K.	Shashua et al., 2009

					Unshaded grass was found to cause only a small air temperature depression and had the highest water requirement. However when the grass was shaded, either by the trees or by the shade mesh, a synergic effect produced greater cooling as well as a reduction of more than 50% in total water use.	
				empirical	Observed reductions in solar radiation at the shaded parking lot site and air-temperature reductions near the paved surface suggest that air-temperature reduction is due in large part to irradiance attenuation attributable to tree shade.	Scott, et al., 1999
				empirical	An excellent prevention of summer heat-load is to plant deciduous trees. In our case the large canopy gives some protections against the direct radiation and, as a consequence, against the extreme heat stress in the midday hours. […] Similarly to earlier studies in Germany, our results show a strong correlation between radiation modifications and changes in the thermal stress, focussing on the role of tree vegetation in these processes [14,24]. The first case shows that (the cutting of trees) logging causes significant raise of the heat stress level, while the second case proves this statement by comparing two points with different exposure and shade conditions.	Gulyás et al., 2006
shade	-	ultraviolet radiation	no	review	Five studies investigated aspects of UVR exposure, a major risk factor for most skin cancers. Studies included the levels of sun exposure on children in schoolyards [85,86], solar radiation variability within different tree canopy structures [87], and personal solar erythemal UV exposure in tree shade [88,89]. Studies in this subdomain were classified as either natural/quasi-experimental or modelling studies	Wolf et al., 2020

					(Table 2). Sun exposure was quantified using either dosimeters for measuring accumulated doses of UVR [90], or sensors for measuring irradiance. In general, the studies found that trees can reduce exposure to UVR, particularly bigger trees witha lower fraction of free sky (or sky view).	
shade	+	walkability	no	theoretical	The Neighbourhood Shadeways program is aiming to increase tree shade/canopy cover to 50% along footpaths and bikeways. City Planning branch partners are providing more shady, comfortable and attractive pathways in areas of the city where more compact urban form and higher residential dwelling targets are being sought. Their support also helps make active and public transport options more attractive, and supplements open space provision and connections. If shady pathways helped to reduce the number of kilometres of private car travel by just 1/100thannually, the greenhouse gas emissions avoided is estimated to be around an additional 25% of what is sequestered directly by the trees themselves.	Plant, 2009
				empirical	Lack of trees along the street leading to the green space was clearly disliked [by elderly people]	Arnberger et al., 2017
sounds of nature	-	perceived stress	no	review	Exposure to nature sounds in a laboratory after a stressful mental arithmetic task speeds some aspects of physiological recovery relative to exposure to other sounds (Alvarsson et al 2010). Specifically, sounds of a fountain and of birds tweeting lowered skin conductance level – a measure of sympathetic nervous activity – more than did sounds of traffic or ambient building ventilation system sounds. However, heart rate variability – a measure of parasympathetic nervous activity – recovered no better during nature	Kuo, 2015

					sounds than during other sounds (Alvarsson et al 2010).	
				empirical	To test whether auditory stimulation has similar effects, 40 subjects were exposed to sounds from nature or noisy environments after a stressful mental arithmetic task. Skin conductance level (SCL) was used to index sympathetic activation, and high frequency heart rate variability (HF HRV) was used to index parasympathetic activation. Although HF HRV showed no effects, SCL recovery tended to be faster during natural sound than noisy environments. These results suggest that nature sounds facilitate recovery from sympathetic activation after a psychological stressor.	Alvarsson et al., 2010
space for trees	+	average tree health	ye s	expert claim	Street tree planting systems which are to produce healthy trees of mature stature must provide a rooting zone which supplies enough water to meet the needs of the trees during a year of drought stress. Depending on the stature of tree involved, that could mean 100m3, 200m3 or more.	Blunt, 2008
				expert claim	see Table 2	Pauleit et al., 2002
				expert claim	Other key issues include tree-infrastructure conflicts, especially with hardscape and underground services, exacerbated in areas with narrow verges and constraints on space. According to one inner suburban participant: 'Probably the main area is the conflicts with infrastructure. We're very tight, we're inner suburban, we're dealing with narrow footpaths in the context of people who want a canopy tree. And it's not always possible' E6 And an outer suburban Council noted: 'The lack of physical space to plant trees, particularly in the verges is probably the biggest	Ely, 2009

					issue.' O2	
				empirical	Moreover, limited growing space in cities is responsible for increased planting of smaller, shorter-lived trees that provide fewer benefits compared to larger trees.	McPherson et al., 2002
space for trees	-	rooting volume	no	empirical	urban consolidation – increasing population density in urban areas results in a greater competition for limited space, and evidence shows that the lack of sufficient space for tree canopies and root systems is a significant factor contributing to tree and limb failure; and	Cunningham, 2011
				empirical	Other key issues include tree-infrastructure conflicts, especially with hardscape and underground services, exacerbated in areas with narrow verges and constraints on space. According to one inner suburban participant: 'Probably the main area is the conflicts with infrastructure. We're very tight, we're inner suburban, we're dealing with narrow footpaths in the context of people who want a canopy tree. And it's not always possible' E6 And an outer suburban Council noted: 'The lack of physical space to plant trees, particularly in the verges is probably the biggest issue.' O2	Ely, 2009
street tree stock	+	costs	no	case study	At the end of 50 years, a standard street tree will have cost £11,902 ($16,078 USD)	Greenblue Urban Report, 2018
street tree stock	-	mental fatigue	no	empirical	Residents living in buildings without nearby trees and grass reported more procrastination in facing their major issues and assessed their issues as more severe,	Kuo, 2001

					less soluble, and more longstanding than did their counterparts living in greener surroundings. Mediation tests and extensive tests for possible confounds supported the attention restoration hypothesis—that green space enhances residents' effectiveness by reducing mental fatigue. [...] Figure 3 shows the distributions of DSB scores for participants living in these two conditions; as predicted, the distribution of scores in the Barren condition is shifted to the left, indicating that participants living in these conditions tended to score lower on DSB than did their counterparts.	
				theoretical	Attention Restoration Theory. Kaplan notes that many settings, stimuli, and tasks in modern life draw on a critical resource for effective functioning: the capacity to deliberately direct attention, or pay attention. The information-processing demands of everyday life—traffic, phones, conversations, problems at work, and complex decisions—all take their toll, resulting in mental fatigue. In contrast, natural settings and stimuli such as landscapes and animals seem to effortlessly engage our attention, allowing us to attend without paying attention. For this and a number of other reasons (see Kaplan, 1995), nature provides a respite from deliberately directing one's attention. As a consequence, Kaplan suggests, time spent in nature allows us to recover from mental fatigue and leaves us with enhanced effectiveness and a sense of rejuvenation.	Kuo, 2001
				empirical	For the relationship between greenness and mental health, the findings suggest a different pathway. The final regression model showed that recreational walking and social coherence were associated with	Sugiyama et al., 2008

					mental health scores and perceived greenness remained an independent, significant predictor of mental health. This suggests that the relationship between perceived greenness and mental health is not totally attributable to walking or to social cohesion. One potential factor explaining this ‘‘unaccounted’’ path is the restorative effects of green or natural environments. Early work by the Kaplans7 34 postulated that contact with nature reduces attention fatigue, which accumulates as the mental effort to maintain attentional focus is sustained. These restorative effects are likely to occur both during activity in natural environments8 and from ‘‘static’’ contact with nature, such as viewing natural landscapes and contact with natural elements.35 36 Considering that the benefits resulting from walking have already been accounted for, the residual association between perceived greenness and mental health may involve restorative effects from static experiences of nature.	
street tree stock	-	negative affect, interpretation and processing	no	empirical	streetscape greenery is at least as strongly related to self-reported health as green areas. […] see Table 4 (streetscape greenery defined as 'amount of greenery visible in the street'; using the Mental Health Inventory (MHI-5))	van Dillen et al., 2012
				empirical	After adjustment for potential confounders, and allowing for unmeasured area-effects using Bayesian mixed effects models, we find an inverse association, with a decrease of 1.18 prescriptions per thousand population per unit increase in trees per km of street (95% credible interval 0.00, 2.45). This study suggests that street trees may be a positive urban asset	Taylor et al., 2015

					to decrease the risk of negative mental health outcomes.	
				empirical	Multilevel regression analyses, controlling for socio-demographic characteristics, revealed that both quantity and quality of streetscape greenery were related to perceived general health, acute health-related complaints, and mental health. Relationships were generally stronger for quality than for quantity. Stress and social cohesion were the strongest mediators. Total physical activity was not a mediator. Physical activity that could be undertaken in the public space (green activity) was, but less so than stress and social cohesion.	de Vries et al., 2013
				empirical	Perceived neighbourhood greenness was more strongly associated with mental health than it was with physical health.	Sugiyama et al., 2008
street tree stock	+	number of trees dying annually	yes	assumption		
street tree stock	-	perceived stress	no	empirical	The study confirmed relationships between quantity and quality of streetscape greenery on one hand and stress and social cohesion on the other hand.	de Vries et al., 2013
street tree stock	+	pests	no	empirical	A limited number of tree pests can also represent a threat to human health. Of particular concern is the oak processionary moth (OPM – Thaumetopoea processionea). The caterpillars of oak processionary moths have thousands of tiny hairs containing a very irritating substance. The moth is a native of southern and central Europe, where predators and environmental factors usually minimise its impact. However, aided by the movement of plants, its range has expanded northwards over the past 20 years	Trees in Hard Landscapes, 2014

street tree stock	+	property value	ye s	empirical	On average, street trees add $8870 to sales price and reduce TOM by 1.7 days. In addition, we found that the benefits of street trees spill over to neighboring houses. […] Of the tree variables evaluated, only number of trees and crown area within 100 ft (30.5 m) of the house were significant (Table 3). The coefficients on both were positive. Recall that crown area within 100 ft (30.5 m) of a house does not include trees that directly front the house. [...] This tree adds $7130 to the price of the house it fronts. However, it also positively influences the price of houses within 100 ft (30.5 m). We drew a random sample of 100 houses from our larger sample of 2608, and found that, on average, there are 7.6 houses within 100 ft (30.5 m) of a street tree. Therefore, a tree with 312 ft2 (29 m2) of canopy cover adds, on average, $12,828 to the value of neighboring houses, and the total benefit of a tree with 312 ft2 (29 m2) of canopy cover is $19,958.	Donovan and Butry, 2010
street tree stock	+	tree canopy	ye s	assumption		
surveillance	-	crime	no	review	many studies have shown that perpetrators avoid areas with greater surveillance and greater likelihood of intervention (e.g., Bennett, 1989; Bennett & Wright, 1984; Cromwell, Olson, & Avary, 1991; Poyner & Webb, 1992). And, substantial research has shown that criminals avoid well-used residential areas where their activities might easily be observed (Coleman, 1987; Macdonald & Gifford, 1989; Merry, 1981; Rhodes & Conley, 1981).	Kuo and Sullivan, 2001
surveillance	-	tree vandalism	no	assumption		
surveillance	-	tree vandalism	no	assumption		

temperature	-	cognitive performance	no	review	Under laboratory conditions with fixed clothing values, studies with the weighted mean of 4.34 °C, 10.04 °C, and 26.68 °C increase in the control air temperature show about % 0.40, % 5.37, and % 7.97 reductions in cognitive performance, respectively. Heat stress causes the most significant decline in the most attention-demanding tasks.	Yeganeh et al., 2018
temperature	+	heat stress	no	empirical	On sunny summer days, microclimatic measures were made in residential streets with low and high percentages of tree canopy cover in Melbourne, Australia. Streets with east-west (E-W) and streets with north-south (N-S) orientation were repeatedly measured for air temperature, relative humidity, wind speed, solar radiation, and mean radiant temperature on both sides of the street between early morning and midafternoon. Physiological equivalent temperature was estimated to indicate HTC throughout the day. In streets with high-percentage canopy cover, air temperature, relative humidity, solar radiation, and mean radiant temperature were significantly lower than in streets with low-percentage canopy cover. The reductions in air temperature under high-percentage canopy cover were greater for E-W streets (2.1°C) than for N-S streets (0.9°C).	Sanusi et al., 2016
temperature	-	mould and dampness (in winter)	no	review	Increased shading can also result in lower indoor temperatures, increasing mould and dampness within buildings and increase energy consumption for building heating in winter.	Salmond et al., 2016
temperature	+	sleep problem	no	review	The systematic review yielded six studies on the effects of rising temperature on sleep. All six studies reported negative effects of higher temperatures on sleep time and sleep quality. In a study using objective measurements of sleep quality, Weinreich et	Rifkin et al, 2018

					al. found that higher ambient temperature was associated with increased severity of obstructive sleep apnea [33]. Over all seasons, an interquartile range increase in temperature (8.6 C) was associated with a 10.1% (95% CI 2.0e18.9%) increase in the ApneaeHypopnea Index [33]. Fukuda et al. established a set of disability weights for sleep problems, other than sleep apnea, to quantify the burden of symptoms and concluded the rising burden of symptoms could be attributable to rising temperatures [34]. In the largest study identified, Obradovich et al. analyzed data on self-reported sleep and objectively measured temperature geolocated to the city leveldwith station-level daily temperature from the National Centers for Environmental Information Global Historical Climatology NetworkeDaily (GHCN-D) from 765,000 participants in a repeated cross-sectional telephone survey conducted annually from 2002 to 2011 in the United States [29]. The authors estimated that a 1 C deviation in monthly nighttime temperatures was associated with an increase of three nights with insufficient sleep per 100 people [29]. In stratified analyses, the authors found that the negative effect of temperature was stronger among elderly and lower income respondents. The study included a projection of the number of nights of insufficient sleep by US geographic location in 2050 and 2099 using existing climate change models.	
tree canopy	-	dispersal around heat	no	review	At night, although the presence of trees may reduce local-scale heat storage and hence release at night, street trees trap radiation within the canyon and reduce ventilation, preventing the dissipation of	Salmond et al., 2016

					sensible heat that has built up during the day. Therefore, while an extensive tree canopy cover may be beneficial during the day, there is a risk of restricted nocturnal longwave cooling leading to slightly higher and more uncomfortable indoor temperatures during the night [38]. It should also be noted that trees change aerodynamic resistance to heat diffusion, and may limit the penetration of breezes and cooling of buildings through open windows at night during summer.	
tree canopy	-	perceived stress	no	review	Exposure to nature has an array of physiological and psychological effects pertaining to relaxation and stress reduction. At one end of a continuum is a highly mobilized state known as “fight or flight;” at the other is a conscious but deeply relaxed state known as the “relaxation response;” and in between is baseline. By stimulating parasympathetic activity, a dose of nature can assist not only in restoring us to baseline from "fight or flight” but also move us past baseline to a state of deep relaxation (Gladwell et al 2012). Moreover, nature’s stress recovery effects are both retrospective and prospective – not only undoing lingering effects of past stressors (e.g., Ulrich, 1991), but preparing us to recover more quickly from future stressors (e.g., Brown et al 2013). The psychological and physiological correlates of stress recovery encompass changes in mood as well as in cardiovascular, endocrine, and immune activity — of these, perhaps the most well-studied in relation to nature are effects on cortisol, blood pressure, and heart rate (see Glaser & Kiecolt-Glaser, 2005, for review of the sympathetic-adrenomedullary and hypothalamic-pituitary-adrenocortical components of	Kuo, 2015

					the stress response and its significance in health, and see Haluza et al 2014, for review of effects tied to nature). At the other end of the continuum, each of the following components of the relaxation response has been tied to nature: parasympathetic dominance (e.g., Gladwell et al 2012), lower-than-baseline heart rate and blood pressure (Park et al, 2010), increases in alpha brain waves (Nakamura & Fuiji, 1990, 1992) and decreases in prefrontal cerebral activity (Park et al 2007; Horiuchi et al 2014). As the prefrontal cortex is the seat of directed attention and executive functioning, it seems likely that this reduction in cerebral activity is the physiological counterpart of the “respite from effortfully directed attention” described in the attention restoration literature as the basis for recovery from attention fatigue (Kuo 2001), and may be a precursor to attention restoration and vitality. The relaxing and stress recovery effects of nature are large, fast, and sensitive to a wide variety of nature exposures: simply sitting in natural surroundings can increase parasympathetic activity by as much as 55% (Miyazaki et al 2014); substantial effects are seen with nature exposures of just 4-5 minutes (Brown et al 13; Gladwell et al 12; Ikei et al 14); and significant effects have been found not only for time spent in natural environments but also for visual only, smell only, tactile only, and sound only forest exposures (Miyazaki et al 2014). That the parasympathetic system is so responsive to even brief views of nature may help explain how residential greenness could have substantial impacts on health: regular micro-restorative experiences of natural views from home or the daily commute might help	

					individuals achieve more relaxed states on an on-going basis; consistent with this idea, blood pressure and salivary cortisol are lower in populations with greener residential surrounds (Markevych et al 2014a; Ward Thompson et al 2012, respectively), as is sense of safety (Kuo et al 1998; Maas et al 2009).	
tree canopy	+	rainfall interception	no	empirical	Analysis of rainfall interception processes at different time-scales indicates that canopy interception varied from 100% at the beginning of the rain event to about 3% at the maximum rain intensity for the oak tree.	Xiao, 2000
				review	Urban trees appear to provide all of the functions associated with SUDS, including the interception and storage of rainfall at source, filtration of pollutants in the canopy and infiltration at the root zone, alongside amenity and ecological value	Stovin, et al., 2008
tree canopy	-	sleep problem	no	empirical	The odds of prevalent insufficient sleep were lower among participants with more tree canopy (e.g. 30% compared with 0-9% tree canopy OR ¼0.78, 95%CI 0.69, 0.88). The odds of incident insufficient sleep were also lower with more tree canopy (e.g. 30% compared with 0-9% tree canopy OR ¼0.87, 95%CI ¼0.75, 0.99). There were no statistically significant associations between prevalent or incident insufficient sleep with open grass or other low-lying vegetation, nor incident sufficient sleep with total green space.	Astell-Burt and Feng, 2019
tree canopy	+	sounds of nature	no	assumption		
tree canopy	+	views of nature	no	assumption		
tree canopy	+	attractiveness of neighborhood	no	empirical	Positively related to perceived attractiveness of links were the following street characteristics: slopes and/or stairs, zebra crossings, trees along the route, front gardens, bus and tram stops, shops, business buildings, catering establishments, passing through parks or the city centre, and traffic volume.	Borst et al., 2008

				empirical	Logistic regression models reported a significant association of odds of walking with density of street trees	Sarkar et al., 2015
tree canopy	+	cognitive performance	no	review	Contact with nature in a variety of forms—wilderness areas, prairie, community parks, window views, and interior plants—is systematically linked with enhanced cognitive functioning as measured by both self-report and performance on objective tests (e.g., Canin, 1991; Cimprich, 1993; Hartig, Mang, & Evans, 1991; R. Kaplan, 1984; Lohr, Pearson-Mimms, & Goodwin, 1996; Miles, Sullivan, & Kuo, 1998; Ovitt, 1996; Tennessen & Cimprich, 1995).	Kuo and Sullivan, 2001
				empirical	Multilevel modeling was used to estimate the associations between green spaces and cognitive development. We observed an enhanced 12-mo progress in working memory and superior working memory and a greater 12-mo reduction in inattentiveness associated with greenness within and surrounding school boundaries and with total surrounding greenness index (including greenness surrounding home, commuting route, and school).	Dadvand et al., 2015
tree canopy	+	deposition on leaves	no	review	Focusing on PM, an early review summarizing the potential magnitude of air pollution reduction via urban vegetation canopies found that average published deposition values (vd in units of cm s−1) corresponded to an estimated 1% reduction of PM10 across urban areas (Litschke & Kuttler, 2008).	Eisenman et al., 2019
tree canopy	-	dispersion around sources of pollutants	no	review	At the scale of a busy arterial road, this review noted that plants can modify air flow (i.e., dispersion), thus increasing PM concentrations near emission sources such as roads.	Eisenman et al., 2019
tree canopy	+	evapotranspiration	no	assumption		

tree canopy	-	noise	no	review	Thick strips of vegetation in conjunction with landforms or solid barriers can reduce highway noise by 6-15 decibels. Plants absorb more high frequency noise than low frequency, which is advantageous to humans since higher frequencies are most distressing to people (Miller 1997).	McPherson et al., 2002
				empirical	Other reasons for having trees in cities, including to reduce smog and dust, to reduce noise, and to show that stores care about the environment, also received very positive ratings and ranked 3, 4, and 5, respectively.	Lohr et al., 2004
tree canopy	+	pollen	no	case study	Finally, the tree species in the city present problems for those with pollen allergies; some 98% of the pollen present in Barcelona is of the type that can set off respiratory allergies.	Cohen-Shacham et al., 2016
tree canopy	+	pollen	no	case study	Finally, the tree species in the city present problems for those with pollen allergies; some 98% of the pollen present in Barcelona is of the type that can set off respiratory allergies.	Cohen-Shacham et al., 2016
				review	We found 40 studies that evaluated tree pollen and VOCs emitted by trees, and their potential adverse effects on health such as the exacerbation of allergy, asthma, and rhinitis symptoms, and related behavior such as suicidal self-directed violence [53]. A range of study designs were employed with cross-sectional approaches being the most prevalent, followed by time series, longitudinal/cohort, modelling, and experimental studies (Table 2). Most studies found that higher pollen concentrations are associated with allergy exacerbation, which may lead to increased anti-allergy drug consumption [54–57] or hospital visits/admissions [58–62]. However, several studies noted that adverse health outcomes are not predicted	Wolf et al., 2020

					solely by pollen concentrations as biophysical factors such as temperature, humidity, and ambient concentrations of air pollutants can produce synergies (e.g., [57,62–66]), and there is variable response associated with a person's age [67]	
tree canopy	+	property value	no	empirical	On average, street trees add $8870 to sales price and reduce TOM [time on market] by 1.7 days. In addition, we found that the benefits of street trees spill over to neighboring houses. […] Of the tree variables evaluated, only number of trees and crown area within 100 ft (30.5 m) of the house were significant (Table 3). The coefficients on both were positive. Recall that crown area within 100 ft (30.5 m) of a house does not include trees that directly front the house. [...] This tree adds $7130 to the price of the house it fronts. However, it also positively influences the price of houses within 100 ft (30.5 m). We drew a random sample of 100 houses from our larger sample of 2608, and found that, on average, there are 7.6 houses within 100 ft (30.5 m) of a street tree. Therefore, a tree with 312 ft2 (29 m2) of canopy cover adds, on average, $12,828 to the value of neighboring houses, and the total benefit of a tree with 312 ft2 (29 m2) of canopy cover is $19,958.	Donovan and Butry, 2010
				empirical	A 10% increase in tree cover within 100 m increases average home sale price by $1371 (0.48%) and within 250 m increases sale price by $836 (0.29%).	Sander et al., 2010
				empirical	Based on the spatial hedonic model, it is estimated that 10% increase in tree cover on street verge above the median cover of 19.66% increases the median house price (AU$ 765,000) by about AU$ 3,250.	Pandit et al., 2012

				empirical	The average sales price increase due to trees was between $1475 and $17.50 ($2869 and $3073 in 1985 dollars) and was largely due to trees in the intermediate and large size classes, regurdless of species.	Anderson and Cordell, 1988
tree canopy	+	residents' perception of tree benefits	no	empirical	The regression coefficients indicate that on-street and off-street vegetation are the two strongest positive influences on esthetic quality. […] larger trees (11" and up) are the most attractive. It appears that newly planted trees need to grow for a while before they have a significant impact on esthetic quality.	Schroeder, 1983
				empirical	Ecosystem services with a more direct effect on people’s health and wellbeing such as recreation and air purification were rated highest. Recreation or visual attractiveness was considered an important benefit of all types of GI except for green roofs (Fig. 5).	Derkzen et al., 2017
tree canopy	+	shade	no	assumption		
tree canopy	+	VOCs	no	case study	Finally, the tree species in the city present problems for those with pollen allergies; some 98% of the pollen present in Barcelona is of the type that can set off respiratory allergies.	Cohen-Shacham et al., 2016
				review	We found 40 studies that evaluated tree pollen and VOCs emitted by trees, and their potential adverse effects on health such as the exacerbation of allergy, asthma, and rhinitis symptoms, and related behavior such as suicidal self-directed violence [53]. A range of study designs were employed with cross-sectional approaches being the most prevalent, followed by time series, longitudinal/cohort, modelling, and experimental studies (Table 2). Most studies found that higher pollen concentrations are associated with allergy exacerbation, which may lead to increased	Wolf et al., 2020

					anti-allergy drug consumption [54–57] or hospital visits/admissions [58–62]. However, several studies noted that adverse health outcomes are not predicted solely by pollen concentrations as biophysical factors such as temperature, humidity, and ambient concentrations of air pollutants can produce synergies (e.g., [57,62–66]), and there is variable response associated with a person's age [67]	
tree canopy	-	wind speed	no	review	The impact of trees on heating energy consumption was addressed in 26 out of 40 papers (65.0%). They reported: i) heating energy savings due to trees playing as windbreaks or reducing wind speed and/or ii) heating penalty due to irradiation reduction by tree shade in wintertime.	Ko, 2018
tree species diversity	+	biodiversity	no	assumption		
tree species diversity	-	vulnerability to pests	no	expert claim	Species diversity may also be necessary for urban ecosystem stability. Can urban forests withstand disturbance (resistance) and how quickly will they return to normal function after disturbance (resilience)? Such stability allows for the long-term provision of ecosystem services (Colding, 2007) in the face of biotic and abiotic change (Hooper et al., 2005). Recent pest outbreaks (Poland and McCullough, 2006) and the environmental changes resulting from climate change (Easterling et al., 2000) highlight the need for species diversity to achieve a resilient urban tree stock as an important contributor to urban ecosystem stability.	Morgenroth et al., 2016
				expert claim	homogeneous plantings are susceptible to pests and diseases, and provide habitat for a limited range of species.	Roetman and Daniels, 2008

tree vandalism	-	attractiveness of neighborhood	no	assumption		
tree vandalism	-	average tree health	no	empirical	The most frequently ranked reason for not wanting trees was that they would be destroyed by vandals, wasting council tax payers' money for no benefit. What seems to be an extremely negative perception of the inevitably of vandalism is, however, perhaps a realistic one as it was ranked most frequently in the least affluent street, where there was considerable evidence of damage to public and private property.	Hitchmough and Bonugli, 1997
tree vandalism	-	municipal resources for trees	no	empirical	The most interesting result from this section is probably the level of vandalism reported. In the UK, up to 30% of newly planted trees were reported to be vandalised, whereas in central European cities levels of vandalism were below 5%. As can be seen from Fig. 7 and 10, in countries where the maximum level of vandalised trees is high, smaller trees are usually planted. Thus, there seems to be a relation between the overall level of investment in new tree planting and the level of vandalism.	Pauleit et al., 2002
ultraviolet radiation	-	physical health	no	review	Ultraviolet radiation (UVR) is the major etiologic agent in the development of skin cancers.	Narayanan et al., 2010
urban densification	-	space for trees	ye s	theoretica l	Added to this is the increasing problem of densification of towns and cities, as people seek to make cities more concentrated, to make use of existing built infrastructure, and to reduce urban sprawl. Densification will reduce the availability of quality space for trees and the urban forest even more, and, more worryingly, in a way that is permanent and not easily reversible	Tarran, 2009
				expert claim	Infill is probably going to be the biggest threat.' O1.. Urban infill (or consolidation) is characterised by ‘two for one’ subdivision of existing allotments,	Ely, 2009

					reducing private tree cover, but also impacting on street trees. More and wider crossovers, additional service connections and reduced frontages result in the loss of existing trees, and a reduction in opportunities for future street tree planting. 'I find the amount of development is increasing, and so we are dealing with street trees being lost, and also limiting the number of trees in front of properties as they are being subdivided. And peoples preference for double driveways or crossovers, 6m crossovers.' W1 ... 'I think there is an issue with the subdivision of blocks. There’s no doubt about it, it’s usually the tree that will suffer in something like this. That to me would be the number one issue for street trees. They are under pressure to get that through planning. It’s more rates.' W4 rban infill leads to smaller allotments, with less private open space, and less vegetation and tree cover. This will place more pressure on Councils for the provision of open space and urban greening in the public realm, including streets. But at the same time, existing street trees are being threatened, and it is becoming increasingly difficult to plant large trees in streets. The problem is exacerbated by an un-coordinated approach to urban consolidation that fails to provide additional public greening to compensate for the loss of private greening. Instead urban infill occurs in an incremental fashion which does not consider the cumulative effects of individual decisions on the urban forest. For urban densification needs to occur it should be accompanied by a coordinated program of urban greening.	

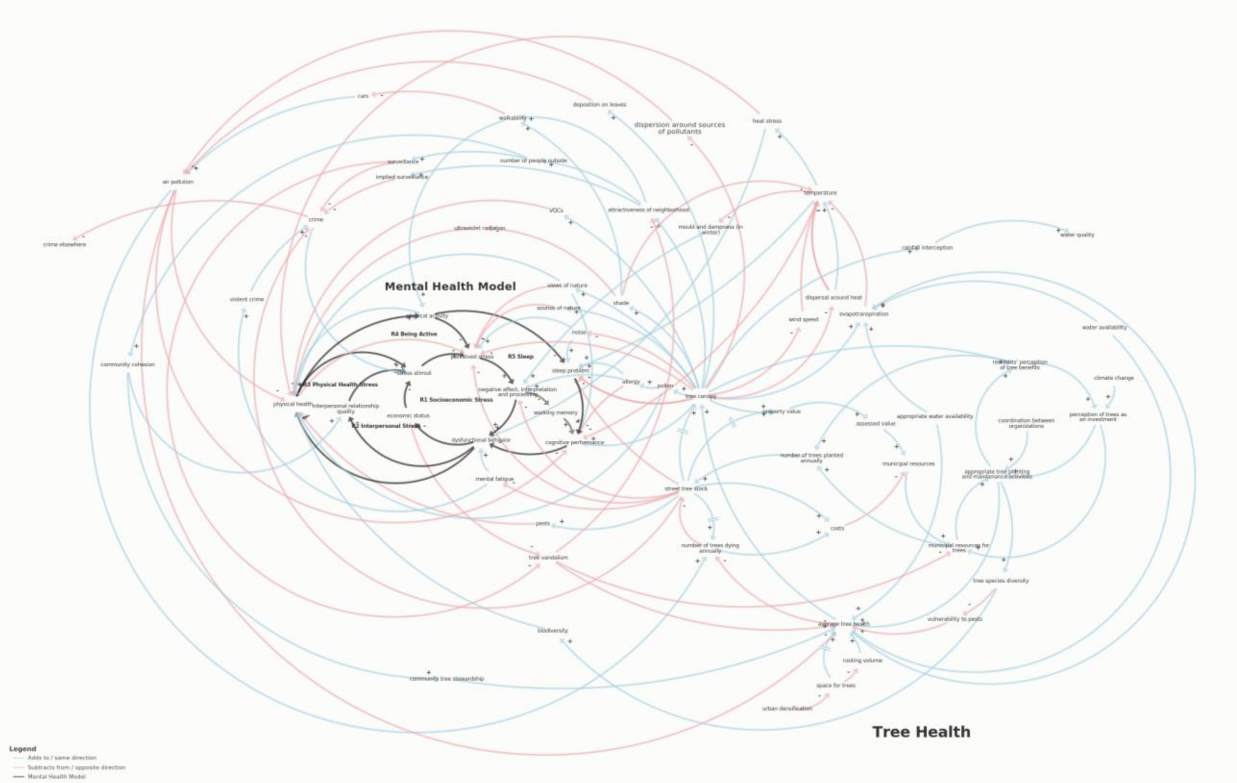
					'And it's part of the government's 20/20 strategy to increase population through urban infill. So we've got that conflict coming in and we're trying to say, with the street tree, and they want big leafy green streets, how do you do that when you've got urban infill and you've got narrow footpaths.' W2 One participant summed up the situation as: 'Space and population: as the population becomes more dense we need more greenery for those benefits. But as the population gets more dense there's more pressure on space, more difficult to grow trees.' E4	
views of nature	+	cognitive performance	no	empirical	As Figure 5 shows, view from home strongly and positively predicts girls' scores on this combined measure, F(1, 76) = 19?4, po0?0001. On average, the greener a girl's view from home, the better she scores overall on di¡erent forms of self-discipline; for each point di¡erence in greenness of view, scores increase by roughly a quarter of a standard deviation, beta = 0?274. Greenness of view explains roughly one-¢fth of the variance in self-discipline scores, R-squared = 0?203.	Taylor et al., 2002
views of nature	-	perceived stress	no	review	As little as five minutes of exposure to images of trees, grass, and fields in a laboratory setting is enough to increase parasympathetic nervous activity and decrease heart rate (Gladwell et all 2012; Brown et al 2013).	Kuo, 2015
				empirical	Forty-six students viewed photos of green and built spaces immediately following, and preceding acute stress induction. Simultaneously recorded electrocardiogram and impedance cardiogram signal was used to derive respiratory sinus arrhythmia (RSA) and pre-ejection period (PEP), indicators of	Van den Berg et al., 2015

					respectively parasympathetic and sympathetic activity. The findings provide support for greater recovery after viewing green scenes, as marked by a stronger increase in RSA as a marker of parasympathetic activity.	
views of nature	+	physical health	no	empirical	Twenty-three surgical patients assigned to rooms with windows looking out on a natural scene had shorter postoperative hospital stays, received fewer negative evaluative comments in nurses' notes, and took fewer potent analgesics than 23 matched patients in similar rooms with windows facing a brick building wall.	Ulrich, 1984
violent crime	+	crime	no	assumption		
VOCs	-	physical health	no	review	Two studies focused on the health impacts of VOCs [83,84], which are emitted naturally by trees. VOCs are an air quality concern because they are precursors to the formation of ozone [13,32]. Yet the effects of VOCs are not always negative, as one study found that smelling VOCs derived from Cedrus deodara can lead to increased relaxation and blood oxygenation with improvements to the respiratory or circulatory system, and decreased blood pressure [83]. Overall, tree pollen and VOCs have been associated with negative health outcomes, but these effects are not consistent across all tree species or urban living conditions, which suggests that these harmful effects can be reduced through tree selection and management practices.	Wolf et al., 2020
vulnerability to pests	-	average tree health	no	case study	a major change to the natural environment—the loss of 100 million trees to the emerald ash borer, an invasive forest pest [..] However, once the borer is detected in a county, often many healthy trees are cut down to prevent its spread. This practice was	Donovan et al., 2013

					particularly common during the early years of its spread.	
walkability	-	cars	no	theoretical	If shady pathways helped to reduce the number of kilometres of private car travel by just 1/100thannually, the greenhouse gas emissions avoided is estimated to be around an additional 25% of what is sequestered directly by the trees themselves.	Plant, 2009
walkability	+	physical activity	no	empirical	Recreational walking seemed to explain the link between greenness and physical health […] Our findings are strongly suggestive of the importance of ‘‘walkable’’ green environments for better health and support findings from a previous study on older people’s health and walkable green environments. The finding suggests that neighbourhood green spaces are conducive to better health, in so far as they are walkable, especially in the case of physical health.	Sugiyama et al., 2008
				review	Saelens, Sallis, and Frank (2003) reported that residents of highly walkable neighbourhoods were more physically active and less obese compared to residents of lesser walkable neighbourhoods.	Borst et al., 2008
wind speed	-	temperature	no	review	The impact of trees on heating energy consumption was addressed in 26 out of 40 papers (65.0%). They reported: i) heating energy savings due to trees playing as windbreaks or reducing wind speed and/or ii) heating penalty due to irradiation reduction by tree shade in wintertime.	Ko, 2018

Appendix 3

Figure 1**:** Detailed causal loop diagram



Appendix 4

Table 1: Positive hypothesized causal pathways connecting street trees and mental health

No.	Pathway	Category
1	Street trees → reduce local temperature (Livesley et al., 2016; Salmond et al., 2016) → reduce heat-related sleep problems (Rifkin et al., 2018) → reduce negative affect	Reduce harm
2	Street trees → reduce local temperature (Livesley et al., 2016; Salmond et al., 2016) → reduce heat-related cognitive underperformance (Yeganeh et al., 2018) → reduce negative affect	Reduce harm
3	Street trees → reduce local temperature (Livesley et al., 2016; Salmond et al., 2016) → reduce heat stress-related morbidity and mortality (Wolf et al., 2020) → reduce negative affect	Reduce harm
4	Street trees → reduce local temperature (Livesley et al., 2016; Salmond et al., 2016) → reduce heat-stress related dysfunctional behaviours (e.g. aggression and violence) (Kuo, 2015) → reduce negative affect	Reduce harm
5	Street trees → reductions in noise (McPherson et al., 2002) → reduce perceived stress (McPherson et al., 2002) → reduce negative affect	Reduce harm
6	Street trees → reductions in noise (McPherson et al., 2002) → reduce noise-related sleep problems (Sygna et al., 2014) → reduce negative affect	Reduce harm
7	Street trees → reductions in air pollution (Eisenman et al., 2019) → improves physical health (Lovasi et al., 2008; Wolf et al., 2020) → reduce negative affect	Reduce harm
8	Street trees → reductions in air pollution (Eisenman et al., 2019) → cognitive performance (Dadvand et al., 2015) → reduce negative affect	Reduce harm
9	Street trees → reductions in ultraviolet radiation (Wolf et al., 2020) → impacts physical health (Narayanan et al., 2010) → reduce negative affect	Reduce harm
10	Street trees → improvements in cognitive performance (Kuo and Sullivan, 2001) → reduce negative affect	Restore capacities
11	Street trees → direct reductions in stress (Kuo, 2015)→ reduce negative affect	Restore capacities
12	Street trees → reductions in mental fatigue and related dysfunctional behaviors (Kuo, 2001) → reduce negative affect	Restore capacities
13	Street trees → reductions in crime (Burley, 2018; Donovan and Prestemon, 2012; Kuo and Sullivan, 2001) → reductions in stress stimuli (Brewin et al., 1999; Green and Diaz, 2007) → reduce negative affect	Restore capacities

14	Street trees → reductions in sleep problems (Astell-Burt and Feng, 2020) → reduce negative affect	Restore capacities
15	Street trees → increased sounds of nature (Kuo, 2015) → reduce perceived stress (Alvarsson et al., 2010; Kuo, 2015) → reduce negative affect	Restore capacities
16	Street trees → increased view of nature (Kuo, 2015) → reduce perceived stress (Kuo, 2015; van den Berg et al., 2007) → reduce negative affect	Restore capacities
17	Street trees → increased view of nature (Kuo, 2015) → improve physical health (e.g. surgery recovery)(Ulrich, 1984) → reduce negative affect	Restore capacities
18	Street trees → increased walkability (Borst et al., 2008; Sarkar and Bardhan, 2019) → improves physical activity (Borst et al., 2008; Sugiyama et al., 2008) → reduce negative affect	Build capacities
19	Street trees → increase is social cohesion (de Vries et al., 2013; Kuo, 2015, p. 201; Maas et al., 2009) → improve interpersonal relationship quality (de Vries et al., 2013; Kuo, 2015, p. 201) → reduce negative affect	Build capacities
20	Street trees → increased environmental biodiversity (Kuo, 2015) → improve physical health by increasing the presence of beneficial bacteria (Kuo, 2015) → reduce negative affect	Build capacities

Table 2: Negative hypothesized causal pathways connecting street trees and mental health

No.	Pathway	Category
1	Street trees → increase pollen exposure (Cohen-Shacham et al., 2016; Wolf et al., 2020) → increase in allergies (Sansone and Sansone, 2011; Wolf et al., 2020) → increase negative affect	Increase harm
2	Street trees → tree limb or tree falls (Cunningham, 2011; Dawes et al., 2018; Kirkpatrick et al., 2012) → reduce physical health → increase negative affect	Increase harm
3	Street trees → reduced dispersion around sources of pollutants increase air pollution (Eisenman et al., 2019) → reduce physical health → increase negative affect	Increase harm
4	Street trees → increased pests (e.g. oak processionary moth) (Trees and Design Action group, 2014) → reduce physical health → increase negative affect	Increase harm
5	Street trees → reduce local temperature (Livesley et al., 2016; Salmond et al., 2016) → increased mould and dampness (Salmond et al., 2016) → increase negative affect (Evans et al., 2000; Liddell and Guiney, 2015)	Increase harm
6	Street trees → increase crime through reduced visibility amongst low-growing canopies (Donovan and Prestemon, 2012) → increase crime → increase in stress stimuli (Brewin et al., 1999; Green and Diaz, 2007) → increase negative affect	Reduce capacities
7	Street trees → block sunlight or desirable views (Flannigan, 2005; Schroeder et al., 2006) → increase negative affect	Reduce capacities
8	Street trees → damage sidewalks (Ely, 2009; Heimlich et al., 2008; Kirkpatrick et al., 2012; McPherson and Peper, 1996) → reduce walkability → reduce physical activity → increase negative affect	Prevent capacity building