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A Systems Perspective on the Interactions Between Urban Green Infrastructure and the Built Environment

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Abstract. This research addresses the intricate dynamics between urban green infrastructure (UGI) and the built environment, focusing on the effects of urban heat islands, building energy demand, and human health. Following the idea of the Socio-Ecological-Technological Systems framework, we investigate key indicators related to green and grey infrastructure and their interactions at the urban scale. We construct a comprehensive causal-loop diagram through an iterative approach involving literature analysis and expert consultation. The outcomes highlight the significance of urban form and green infrastructure in connecting indoor and outdoor spaces. This research enhances the understanding of systemic behavior in the urban fabric and offers insights into the complex interactions between UGI and the built environment. The approach underscores the value of iterative modeling, fostering collaborative efforts and providing a foundation for further system modeling. Future research should focus on quantitative validation of the identified connections. Additionally, connection strengths and spatial elements would be valuable extensions of the presented system model.

1. Background

The rising global urban population, predicted to increase to 68% by 2050 from the current 55% [1], and the increasing impacts of climate change impose great challenges for cities worldwide [2]. Climate change mitigation and adaptation are key for transforming cities into resilient urban spaces. Urban Green Infrastructure (UGI) is one of the main levers for both mitigation and adaptation [3]. However, the way to achieve this transformation is fuzzy, and a clear solution is hard to identify. Rather, collaborative and co-designed solutions must be developed for the "wicked" problems within urban spaces, such as flooding, heat stress, and drought [4]. Such solutions must address multiple challenges in parallel without imposing disproportionate trade-offs to other sustainability aspects. To achieve this goal, considering interactions in urban space is inevitable. For instance, urban heat islands (UHI) influence the energy demand of buildings, human thermal comfort, and human health. On the one hand, green infrastructure is a promising multifunctional solution to mitigate these effects and adapt to increases in UHI caused by climate change and urbanization [5]. On the other hand, reduced tree growth and vitality as well as increased mortality rates in the urban environment can significantly reduce these ecosystem services (ESS). Trees are also associated with certain disservices, such as allergies that may affect human health, especially in urban areas. Factors that increase the release of pro-inflammatory mediators by pollen are ozone, drought, Volatile Organic Compounds and fungal spores [6–8]. Pollutants, on the other hand, directly affect humans by damaging the barrier function of the mucosa and skin, paving the way for allergic inflammation [9]. Climate change is also prolonging the flowering phase and increasing pollen allergenicity [10]. Clarifying interactions like these improves the understanding of possible solutions to the pressing urban environmental issues but needs a systematic overview of relevant indicators and their influences.

2. State of research and research goal

McPhearson et al. propose the Socio-Ecological-Technological Systems (SETS) framework for this task [11]. The SETS framework is a holistic and multidisciplinary approach to understand and address complex environmental and societal challenges. It integrates social sciences, ecology, and technology perspectives to analyze interactions that affect urban ecosystems. The framework emphasizes the dynamic interactions, relationships, and interdependencies between different scales and subsystems [3]. Changes in one dimension can have cascading effects on the others. We adopt the SETS framework as a system thinking approach that emphasizes that causes and their effects are often less straightforward than one might intuitively expect. Such an approach is thought to facilitate the understanding of systems and processes as emerging from a dynamic array of interrelated factors, which can have both expected and unintended consequences [12].

To the best of our knowledge, there has been little work on applying such an approach to the urban green-grey nexus. Bi et al. review assessment frameworks at the building and urban scales. The review points out that the social dimension is underrepresented and that the interaction of different urban scales is hardly considered. Furthermore, a narrow definition of sustainability and limitations in the aspects considered are criticized. A systemic approach to consider indoor and outdoor air pollution is elaborated. The authors propose a step-by-step integration of relevant subsystems, starting with building systems and moving to traffic, vegetation, and urban ecosystems. However, a generic basis for the integration of further aspects is needed [13]. Berry et al. show that cross-sectoral interactions are rarely considered in research, resulting in the neglect of potential synergies and trade-offs from various mitigation and adaptation measures. Specifically, they note that although green infrastructure exhibits significant potential for multiple benefits, it is often unrecognized and underutilized. To fully realize this potential, they emphasize the essential need for interdisciplinary collaboration [14].

As there has only been little attention to the topic of green-grey interactions in research, this study shows how the effects of interventions in such complex systems can be qualitatively assessed and explained. We hypothesize that indicators related to UGI are highly interconnected to the energy demand of buildings, as well as human comfort and human health on a neighborhood level. To verify this, we aim to answer the following research questions:

- Which indicators interact in a SETS framework of the urban vegetation-building nexus?
- What is the direction of the connections between these indicators?
- What are highly interconnected indicators in this system?
- Which new aspects for quantitative investigation can be derived from a qualitative system?

A systems model of this nature will serve as a holistic framework to advance our understanding and promote the development of essential knowledge necessary for planning inclusive green-grey urban landscapes, with considerations of the synergies and trade-offs and evaluating the efficacy of specific interventions that can facilitate sustainable urban futures.

3. Methodology

The research approach is structured in two phases: First, data collection with analysis, and second, causal-loop diagram development. A comprehensive review of existing literature on the energy demand of buildings, human comfort, and human health in relation to UGI is conducted for the indicator selection. Indicators are identified from the literature and selected based on their significance, reliability, and relevance to multi-level analysis. We focus on quantifiable indicators to improve the understanding of directed interactions in the second step of the methodology. Urban neighborhoods in Germany are the focus and system boundary of this research. The next phase involves establishing the connections between the indicators identified in the previous phase. Additionally, linking indicators are introduced if necessary to clarify indirect relationships between main indicators. An extensive literature analysis traces relationships, dependencies, and feedback loops. Conceptual mapping techniques are employed to visualize the potential causal connections between energy demand, human comfort, and human health indicators. The resulting causal-loop diagram visually represents the causal relationships and feedback loops between the indicators. The diagram is developed iteratively, involving a continuous process of refinement and validation to ensure its accuracy and coherence with the established literature. For this step, we use the open-source tool Kumu [15]. The results were subjected to expert validation to enhance the credibility of the causal-loop diagram. Therefore, domain experts in ecology, environmental health, and urban planning were consulted. Their feedback and insights were incorporated to improve the causal-loop diagram. For interpretation, we focus only on parts of the causal-loop diagram, as the resulting graph is highly interconnected and, therefore, hard to visualize as a whole. This has been an approach in other works with causal-loop diagrams as well [16]. Finally, we select indicators with non-obvious connections and investigate how the developed causal-loop diagram can be used to explain the connection between them.

4. Results and discussion

Indicators that are deemed relevant for our research questions are outlined in section 4.1. Afterward, section 4.2 introduces the indicator connections and their orientation. Section 4.3 investigates the number of connections to show highly interconnected elements. To allow for a more concise interpretation of the causal-loop diagram, we split it into smaller parts and show how it can be used to derive hypotheses for further research in section 4.4.

4.1. Main indicators

Outdoor thermal comfort is an important factor for human biometeorology [17]. Poor thermal comfort compromises people's health status and general well-being, resulting in more serious health problems. It also affects people's mood, memory, ability to learn and concentrate, and job performance [18]. Thus, it refers to the social side of the SETS framework. Air temperatures only cannot adequately describe the perception of heat by urban residents [19]. It requires a thermo-physiological assessment of the urban environment by considering air temperature, humidity, radiation, wind, human metabolic exchange rate, and other individual-related parameters (e.g., age, gender, medical background). Outdoor thermal comfort indices reflect such a comprehensive assessment. This holistic understanding of the thermal environment's impact on human heat balance offers valuable insights for optimizing UGI design, ultimately fostering the creation of urban spaces that are thermally comfortable. We quantify the outdoor thermal comfort using the Universal Thermal Climate Index (UTCI). UTCI is a thermal index based on thermo-physiological responses covering the entire climate range from -50 to $50\,^{\circ}\mathrm{C}$ [20]. The UTCI is designed to assess the actual impact of the thermal environment on a reference human body based on a heat balance model. The UTCI assessment scale defines thermal stress categories based on the physiological response of a human body to the prevailing environmental conditions. A UTCI range of +32 to +38 °C indicates strong heat stress, +38 to +46 °C very strong heat stress, and above +46 °C indicates extreme heat stress.

Indoor thermal comfort plays another major role for human well-being, as humans spend up to 90% of their time indoors [17, 21]. Therefore, buildings shall maintain a comfortable indoor environment. Several cooling strategies can support this: active systems, such as air conditioning, use electrical energy to lower indoor temperature. Passive strategies summarize cooling by natural heat dissipation (e.g. night flushing), and heat gain prevention (e.g., window blinds, outdoor shading). This already makes clear, that indicators can be connected to several dimensions of the SETS framework. Indoor thermal comfort itself refers to social aspects, but if external measures for maintaining comfort are utilized, the technical or, in the case of trees, the ecological disciplines are involved. The Predicted Mean Vote (PMV) quantifies users' individual indoor heat stress experience. It ranges from −3 (cold stress) to +3 (heat stress). A value close to zero indicates a well-balanced indoor thermal comfort [22].

Building energy demand is still the most important technological aspect of climate change impact caused by the built environment [23]. In the temperate climate of Germany, heating energy demand plays a major role. Only a small share of residential buildings is equipped with cooling units [24], but this share is rising with the increasing impact of climate change and UHIs getting more intense. Additionally, buildings demand energy for lighting and hot water preparation. Building energy demand is usually given in kWh per square meter gross floor area and year.

Global warming potential (GWP) quantifies the relative impact of different greenhouse gases on global warming over a specified time period, usually 100 years. It is expressed in carbon dioxide equivalents (CO_2e), which allows to sum up different gases in terms of their heat-trapping capacity. In the past, most greenhouse gases from buildings were set free during their operation. With increasing insulation standards, this share is lowering but still most significant today [23]. Thus, lifecycle-based consideration of buildings is crucial to capture their whole impact. This includes building construction, operation, maintenance, demolition, and disposal. Life Cycle Assessment is a standardized method to calculate the total emissions over the entire life span of a building. This holistic approach allows to understand the overall environmental impact of a building and helps to make informed decisions regarding construction materials, design, and energy systems [25].

Urban tree population dynamics significantly shape their contribution to ESS within urban areas, aligning with the SETS framework's foundational principles. Research highlights the benefits of urban trees, including carbon sequestration, mitigating the UHI effect, managing stormwater, improving air quality, and contributing to cultural values and aesthetics, all of which significantly influence human health and well-being [26]. Through shading and transpiration, they reduce surface and air temperatures [27], mitigate rainwater runoff [28], filter air pollutants [29], store carbon [30], and provide wind and noise buffering [26]. However, to sustain these benefits, it is essential to ensure the vitality of trees and continually increase the number of newly planted trees, surpassing losses from mortality and removal. Therefore, acquiring data on species-specific growth velocity, vitality, and mortality is essential for anticipating future changes and fulfilling the planting needs of urban tree populations and ESS [31–33]. This indicator is defined by *Tree Growth* and *Mortality Rate [%]*

Urban green allergenicity highlights the risk that ornamental trees in urban areas may pose to human health in terms of allergies [34]. However, pollen causes allergies and can block antiviral reactions, weakening immunity against certain respiratory viruses [35]. As it directly affects humans, this indicator is mostly related to the social part of SETS. As green spaces have positive effects on heat, pollution, and human well-being [36], ornamental trees with high

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allergenic potential are often used for this purpose [34, 37], which can lead to allergenic rhinitis, conjunctivitis, hay fever, allergic asthma, and dermatitis [38]. To locate sites in the city where high allergenicity of urban greenery is expected, indices such as the IUGZA [39] or AIROT [40] are used. These range from 0 (minimal risk) to 1 (maximum risk).

Tree crown geometry, encompassing crown shape and size, is pivotal in enhancing the local climate. For instance, the efficacy of trees in providing shade and filtering solar radiation relies heavily on factors such as canopy shape, density, and overall tree structure [41]. As a result, crown geometry and shape changes can directly impact the extent of ecosystem service provision. The accurate crown volume is a valuable proxy for estimating critical factors like leaf area, transpiration, and the filtration of fine particles [42]. Gratani and Varone [43] identify crown volume as the most significant indicator in explaining changes in air temperature beneath the tree canopy. Therefore, accurately calculating a tree's crown geometry is essential for precisely estimating growth parameters and ecosystem services.

4.2. Indicator connections

This section introduces the connections between the selected indicators and their indirect linkages. We only choose quantitative or categorical aspects, as they allow us to assign a direction to the connections. These directions can either be directed or mutual. For directed connections, we assign whether increases or decreases happen when two indicators interact. Mutual connections also represent interactions between two indicators, but currently, the direction is unclear or one of the indicators is qualitative, where no continuous scale is available to assign increases or decreases. Table 1 shows the connection types used for the causal-loop diagram and their interpretation. The following subsections explain the connections of each main indicator and build a separate causal-loop diagram for building energy and emissions, outdoor thermal comfort, urban tree growth, urban tree population dynamics, and pollen. Furthermore, we classify the indicators as adjustable, affected, or linked. These classes help to analyze the results. Affected means, that indicator adjustment happens mostly indirectly through other actions (e.g. Global Warming Potential), while adjustable indicators are potential levers within the system (e.g. Tree Species Selection). Linking indicators are necessary to capture indirect relationships between adjustable and affected indicators. We introduce them where additional information on interaction processes is necessary. After showing causal-loop diagrams for each aspect, we combine them in section 4. Indicators are written italics and capitalized in the following text.

Table 1. Connection types between start (base) and end of the connection (connected).

Type	Direction	Interpretation
$++$	$\xrightarrow{\text{directed}}$	Increasing the base aspect increases the connected aspect.
$+-$	$\xrightarrow{\text{directed}}$	Increasing the base aspect decreases the connected aspect.
$+/-$	$\xleftrightarrow{\text{directed}}$	There is a connection in both directions.
$+/-$	$\underline{\text{mutual}}$	There is a connection, but we do not know the direction.

4.2.1. Building energy, global warming potential and indoor thermal comfort

Shading from Trees and Buildings can reduce incoming solar radiation and thereby improve *Indoor Thermal Comfort* during summertime [44, 45]. As *Indoor Thermal Comfort* is given as PMV, reducing overheating means lowering the value. Thus, we establish a (+ −) connection. On the contrary, during wintertime *Heating Energy Demands* rise, as there is less solar radiation to heat the indoor space (+ +) [46]. Shading also increases *Lighting Energy Demands* (+ +) and may decrease the *Efficiency of Renewable Energy Production with Photovoltaic* (PV) systems (+ −). Improving PMV by e.g. shading allows users to reduce their cooling needs and thus lower *Cooling Energy Demand* (+ −). If buildings are equipped with active cooling systems, these can also improve *Indoor Thermal Comfort* while facing the trade-off of increasing *Cooling Energy Demand* (+ −). The *Urban Heat Island Effect* causes heat storage within densely built cities [47]. On the one hand, this results in reduced *Heating Energy Demands* (+ −) but on the other hand, *Cooling Energy Demands* increase (+ +) and *Indoor Thermal Comfort* may suffer (+ +) [48]. The *UHI* is strongly driven by the urban morphology, where *Building Height* and *Density* reduce *Sky View* (+ −), which causes less nighttime cooling. Dense tree canopies cause the same effect, which may be outweighed by evapotranspirational cooling through trees [49]. All increases

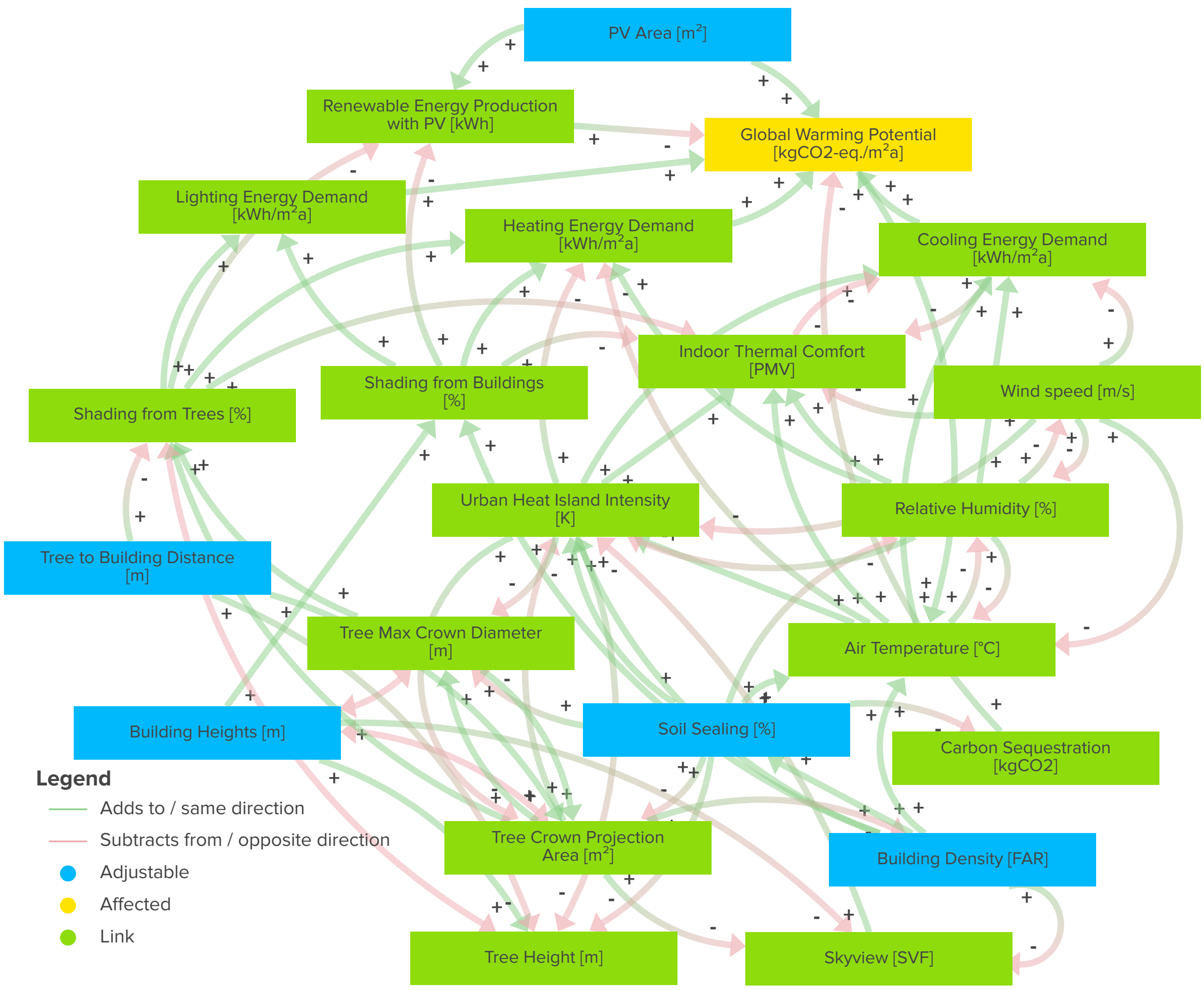

Figure 1. Indicator connections related to *Global Warming Potential*, *Indoor Thermal Comfort*, and *Energy Demand* of Buildings.

in energy demands lead to an increase of *GWP* in the end (+ +), as renewable energy sources do not fully power the current German electricity grid, and a lot of houses still use gas or oil for heating [24]. One way to lower *GWP* of buildings is to install PV Systems on roofs or façades, thereby increasing the *Renewable Energy Production*. Thus, we establish a (+ +) link between *PV Area* and *Renewable Energy Production*, while the renewable energy leads to a decrease in *GWP* (+ −). One should be aware that PV systems must be considered from a lifecycle perspective. This means that the production of PV panels and their maintenance and disposal add to the *GWP* of the building (+ +), and planers need to ensure that there is a positive balance in the end. *Carbon Sequestration* by trees, shrubs, or unsealed grass surfaces reduces the *GWP* (+ −) [50]. Figure 1 shows the causal-loop diagram with the explained indicator connections.

4.2.2. Outdoor thermal comfort

Outdoor thermal comfort (OTC) is heavily influenced by *UHI* intensity and the urban form. Typically, the most intense *UHIs* occur under low *Wind Speed* and low cloud cover [51]. However, urban parameters like open space, land cover, street geometry, and built form play a pivotal

Figure 2. Indicator connections related to *Outdoor Thermal Comfort*.

role in shaping microclimates that impact parameters like *Mean Radiant Temperature* and *Wind Speed*, both of which are crucial determinants of OTC [19]. The changes in surface energy balance due to the replacement of natural, vegetated surfaces by impervious surfaces leads to modifications in radiative, thermal, moisture, and aerodynamic characteristics of the surrounding environment resulting in variation of the *UHI* intensity and *Air Temperature* [52]. Impervious surfaces absorb and retain heat, increasing the *Surface Temperatures* and higher sensible heat flux. Thus, higher levels of *Surface Sealing* will have a detrimental effect on the OTC, represented as a (+ −) link. Thus, higher *Air and Surface Temperatures* due to high levels of *Surface Sealing* and *UHI* can intensify outdoor heat exposure and thermal discomfort for pedestrians (+ +). Studies have demonstrated that a combination of *Building and Tree Shade* can efficiently mitigate heat stress, often resulting in *UTCI* values falling within the "moderate thermal stress" category [53]. Tree shade offers a superior cooling effect compared to building shade due to the dual cooling mechanism of shading and evapotranspiration [54]. Dense, foliated tree crowns reduce the transmissivity of incoming solar radiation. Canopy-related attributes, such as *Leaf Area Index (LAI)* and *Crown Projected Area*, have been identified as the most influential factors in enhancing OTC [55], which explain the (+ −) link for the causal-loop diagram. However, trees' cooling services are highly contingent on their growth conditions and vary significantly across different species, as the mutual connections (+/−) indicate. Figure 2 shows the causal-loop diagram with the explained indicator connections.

4.2.3. Tree crown geometry growth

As urban trees can significantly mitigate heat stress, investigating urban trees' regeneration, growth, and mortality and evaluating the influential factors is crucial to achieving this aim. Unlike typical forest trees, urban trees predominantly grow in small planting pits characterized by tightly packed and sealed soils [56]. These pits often have limited water availability, reduced oxygen intake, subpar soil conditions, fewer mycorrhizal associations, and a constrained tree rooting area [57, 58]. Additionally, aboveground space can be restricted by factors like power lines, nearby buildings, and trees or pruning requirements for traffic safety. The canopies of trees, particularly the crowns of individual trees, which include their size and shape, significantly affect ESS. Recent assessments in urban forestry studies have utilized estimates of crown radii and length to determine tree crown dimensions, assuming canopies adopt a simplified cylindrical form [59]. When light competition prevails, a cylindrical canopy shape could result from allocating biomass in the stem, leading trees to grow taller to maintain a competitive position when there is limited space for crown expansion [60]. For example, *Tree to Tree Distance* or *Tree to Building Distance* have a directed (+ −) relation to *Tree Height*. Furthermore, increasing *Building Heights* can lead directly (+ +) to a *Tree Height* increase. This competition from neighboring trees in urban environments results in more significant variability in *Tree Crown Shapes* (e.g. *Tree to Tree Distance* or *Tree to Building Distance* can change (+/−) *Tree Crown Shapes*) [61]. Figure 3 illustrates the causal-loop diagram encompassing the adjustable and linking indicators associated with tree growth. This depiction highlights that, rather than an array of tree-specific characteristics, certain local environmental factors, like the *Distance to Neighboring Buildings or Trees*, significantly impact the urban *Tree Growth*.

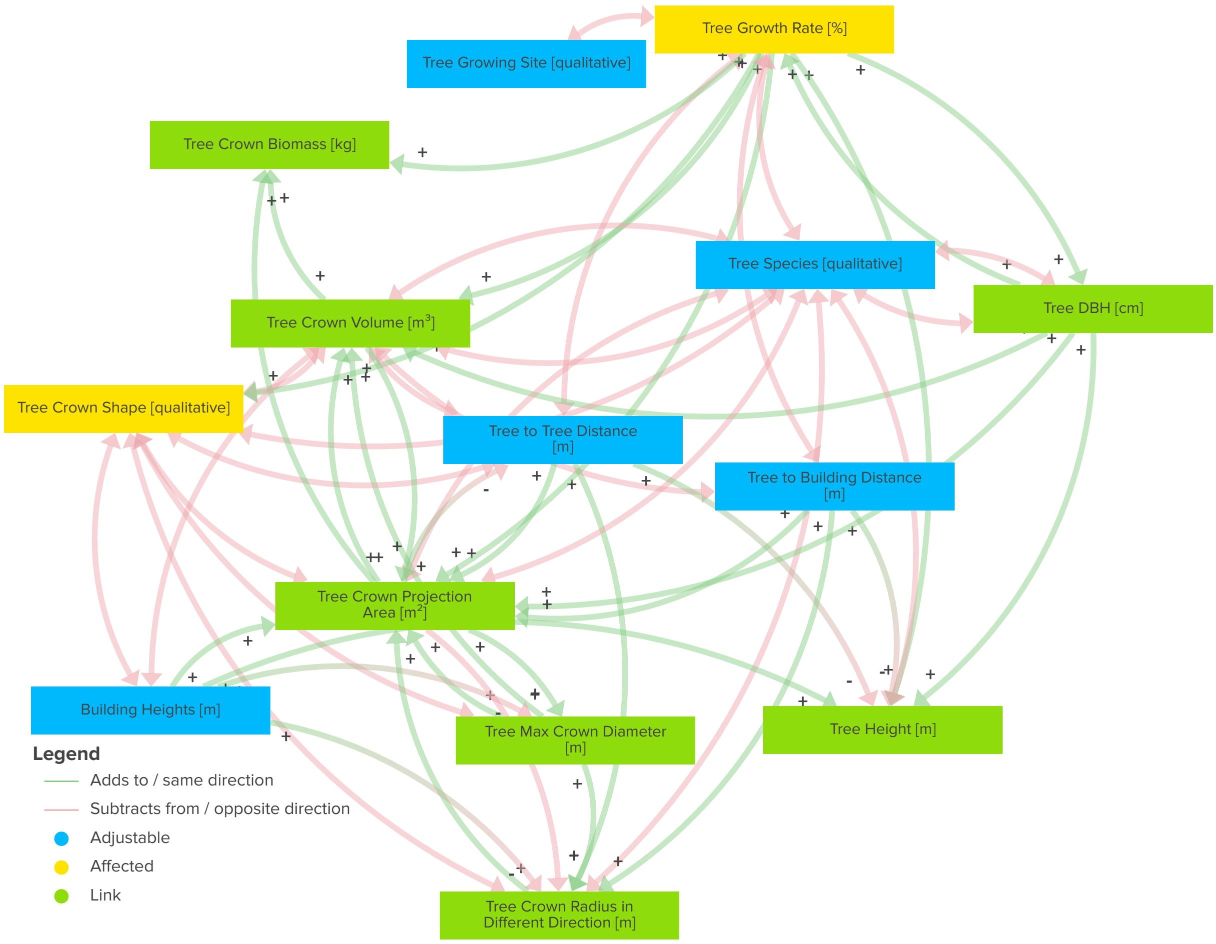

Figure 3. Indicator connections related to urban tree growth indicators, such as *Tree Crown Volume*, *Tree Max Crown Diameter*, or *Tree Height*.

4.2.4. Urban tree population dynamics and stress factors

Continuous urban transformation threatens the sustainability of urban trees stock in delivering beneficial ESS. Urban environment stressors such as building density, heavy traffic, construction activities, compacted soils, and pollution [62–64] can put a negative effect on growth of urban trees or specifically on the canopy growth (see section 4.2.3). Under severe conditions, these stressors may result in tree mortality. In the following, the indicators that could impact the *Tree Growth* and *Mortality Rate* are explained. *Tree Species* plays an important role in the dynamics of *Tree Growth* and *Mortality Rate*. Trees react to stressors differently based on their physiological characteristics. For instance, species like *Acer platanoides* (Norway maple), *Acer pseudoplatanus* (sycamore maple) or *Robinia pseudoacacia* (black locust) are classified as tolerant drought species in urban areas [61, 65]. While *Alnus glutinosa* (common alder), *Populus nigra* (black poplar), *Salix alba* (weeping willow), and *Betula pendula* (silver birch) showed high sensitivity under drought conditions [64]. This explains the mutual (+/−) connection type between this indicator and *Tree Growth / Mortality Rate*. Studies on *Tree Growth* have explored the roles of *Tree Age*, *Tree Diameter at Breast Height (DBH)*, and *Tree Height* [66, 67]. These studies show that there is generally a positively directed connection (+ +) between tree *Tree Age*, *Tree DBH*, and *Tree Growth Rate* in less disturbed environments with low inter-tree competition [59]. However, research on *Tree Mortality*, specifically regarding *Tree Age* and *Tree DBH*, is less extensive and exhibits varying results depending on *Tree Species* and growing conditions. For instance, Roman et al. found a negative correlation between *Mortality Rate* and tree diameter, suggesting that larger, older trees have lower *Mortality Rates* [68]. In contrast, Haase et al. noted that older street trees have higher *Mortality Rates* [63]. However, older trees generally exhibit greater resistance to mortality from drought and heat stress [69]. Consequently, we consider the connection between *Tree DBH* and *Tree Mortality Rate* as directed (+ −) and between *Tree Age* and *Tree Mortality Rate* as mutual (+/−). The relationship between *Tree Height* and *Growth / Mortality Rate* is species-specific and has shown mixed or insignificant correlations in previous studies, leading us to consider it a mutual connection. *Tree Vitality* significantly influences *Tree Growth* and *Mortality Rates*, reflecting the tree's health and survival capacity [63, 70]. Tree vitality levels (Vst) are categorized on a four-point scale (Vst I - No or slight damage, Vst II - Moderate damage, Vst III - Severe damage, Vst IV - Extreme damage or dead) [71]. This explains the chosen connection type for *Tree Vitality*, with a directed (+ −) link to *Tree Growth Rate* and a directed (+ +) link to *Tree Mortality Rate*. The *Tree Growing Site* indicator influences both, *Tree Growth* and *Mortality Rates*. This indicator characterizes the physical environment in which a tree is located, encompassing factors like *Soil Sealing* and *Soil Moisture Content*. Numerous studies have shown that unfavorable soil conditions, including soil structure, aggregate stability, bulk density, porosity, and soil sealing, can hinder tree growth [72–74]. Hence, we establish a directed (+ −) connection between *Soil Sealing Rate* and *Tree Growth Rate*, and a directed (+ +) connection between *Soil Moisture Content* and *Tree Growth Rate*. Similarly, when considering the same indicators for *Tree Mortality Rate*, we apply a directed (+ +) connection with *Soil Sealing Rate* and a directed (+ −) connection with *Soil Moisture Content*. Moving to climate variables, such as *Air* and *Surface Temperature*, supported by

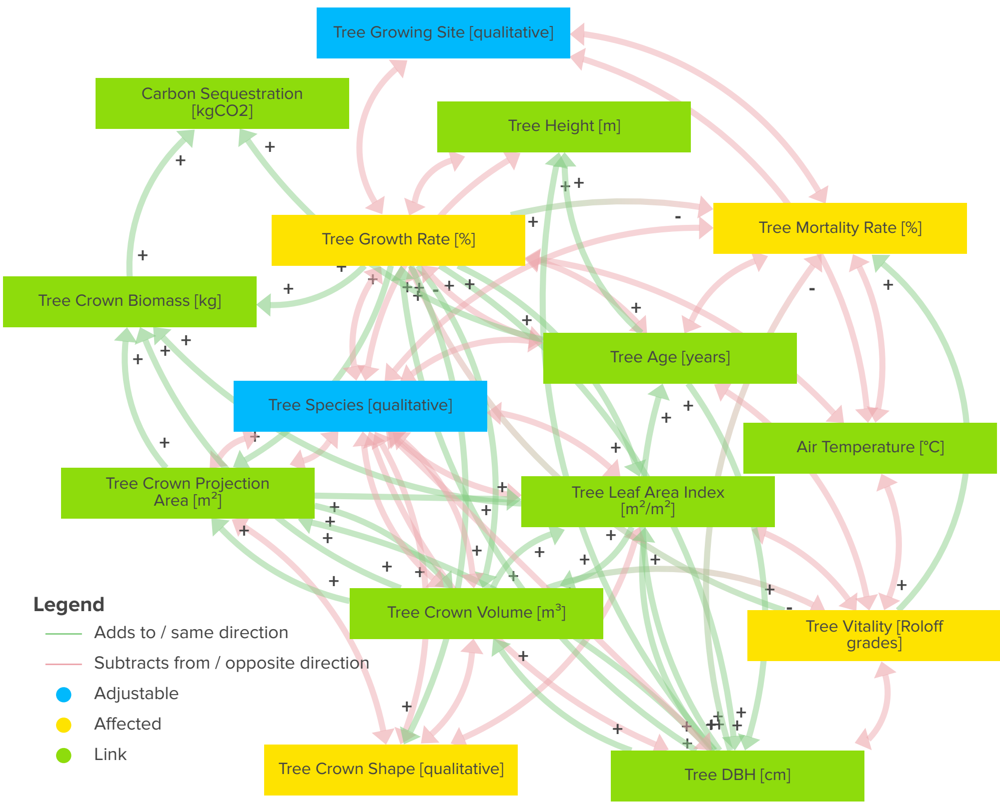

Figure 4. Indicator connections related to urban tree ecosystem services.

numerous studies (e.g., [75, 76]), we establish a directed (+ −) connection type between *Air / Surface Temperatures* rise and *Tree Growth Rate*. Conversely, we establish a directed (+ +) connection between *Air Temperature* rise and *Tree Mortality Rate* due to elevation of water deficit stress. When considering *Relative Humidity* and *Wind Speed*, we could not find sufficient evidence to determine a clear positive or negative correlation with *Tree Growth* and *Mortality Rate*. Thus, we choose a mutual (+/−) connection type for this indicator. Lastly, as *UHI* is influenced by the intensity of the temperature climate variables, we establish a directed (+ −) connection type between *Tree Growth Rate* and a directed (+ +) connection type with *Tree Mortality Rate* in response to the rise of this phenomena. Figure 4 shows the causal-loop diagram with the explained indicator connections.

4.2.5. Spatial and temporal patterns of pollen

The prevalence of environmental allergies has increased significantly over the last few decades, particularly in urban areas [77]. Moreover, the rising trend in allergies is worrying from a global warming perspective, as global warming and the associated *UHI* are expected to change the phenology of plants. *Air Temperature* and total pollen production have a direct positive connection (+ +), resulting in longer growing seasons and an increase in total pollen production [10, 78]. However, these variations are difficult to predict, and taxon-specific [79, 80]. In addition to *Air Temperature*, other meteorological factors such as *Rainfall* and *Relative Humidity* have a directed negative connection (+ −) with the occurrence of airborne pollen allergens [79, 81]. Urban areas, with their warmer temperature, increased CO_2 levels, and air pollution are changing the *Pollen Concentration* in the air and the allergenicity of pollen [82]. Furthermore, pollen can attach to diesel exhaust particles and particulate matter, causing a stronger allergic effect when they enter the respiratory tract [82]. Another aspect of urban areas is the *Potential Dispersability of Pollen*. Buildings have a mutual connection (+ −) with the dispersion of Pollen through turbulence and barrier effects of buildings. In this context, tall buildings and narrow streets can

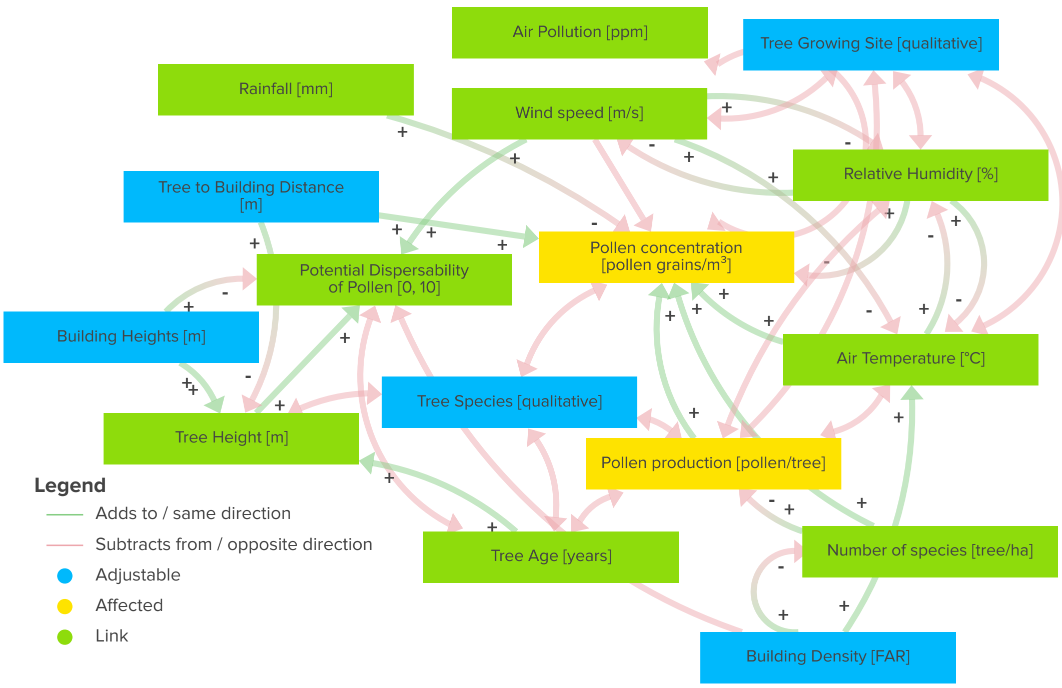

Figure 5. Indicator connections related to spatial and temporal patterns of pollen.

potentially prevent pollen dispersal or promote isolated *Pollen Concentration* while open parks and wide streets promote free dispersal [83]. As mentioned above, *Tree Species* has a mutual connection (+/−) with pollen's allergenicity. In addition, species diversity also significantly impacts allergenicity in cities. While high species diversity often has a positive impact on the quality of life in cities [84], too much abundance of some species can have adverse effects on people living there [34]. For instance, many ornamental trees have high allergenic potential and are commonly used in public spaces, exacerbating pollen occurrence [34, 37]. Birch, for example, has a higher airborne *Pollen Production* compared to other taxa. Therefore, *Pollen Production* per tree is also a crucial factor. This also has a direct positive connection (+ +) with the number of individuals belonging to a species because the more individuals, the more pollen is produced [85]. It is influenced by taxon, site conditions, the number of flowers and inflorescence of the plant, and whether the tree forms in a cluster with other individuals or stands alone [86]. Thus, closely clustered trees have lower reproductive success [87]. Pollen production and tree age have a mutual connection (+/−), as the flowering phase begins at different times depending on the tree species. Although pollen production increases over the years for most trees, there is no infinite increase in pollen production [88]. Figure 5 shows the causal-loop diagram with the explained indicator connections of this section.

4.3. Number of connections

Figure 6 shows the combination of all indicators and connections explained in the previous section. To clarify the question of which indicators are most connected, we count the number of connections associated with each indicator in a network analysis. However, this degree of connection needs careful interpretation, as it does not mean that highly connected indicators are more influential than others [89]. Nevertheless, the degree of connection gives an impression of the indicators for which a particularly high number of interactions and a corresponding need for further research can be expected. The *UHI* intensity and *Outdoor Thermal Comfort* index stood out with the most connections (34 and 30). Two tree-related indicators, *Tree Crown Projection Area* and *Crown Volume*, displayed substantial connectivity with 29 and 28 connections, respectively. Following up, the *LAI* had 26 connections. Other tree-related indicators, including *Tree Growth Rate*, *Tree Species*, *Tree DBH*, *Tree Age*, *Tree Vitality*, *Crown Radius in Various Directions*, *Tree Mortality Rate*, *Crown Shape*, and *Tree Height*, were less interconnected, with connection counts ranging from 23 to 13. In the context of abiotic indicators, *Soil Sealing* and *Soil Water Content* displayed 26 and 24 connections, respectively. Among climate indicators, *Air Temperature* reached a maximum with 19 connections, followed by *Relative Humidity*, *Surface Temperature*, and *Wind Speed*, with 16, 14, and 13 connections respectively. Indicators such as *Wind Speed*, *Tree Height*, *Tree Crown Shape*, and *Tree Mortality Rate* showed a more limited connection number of a total of 13.

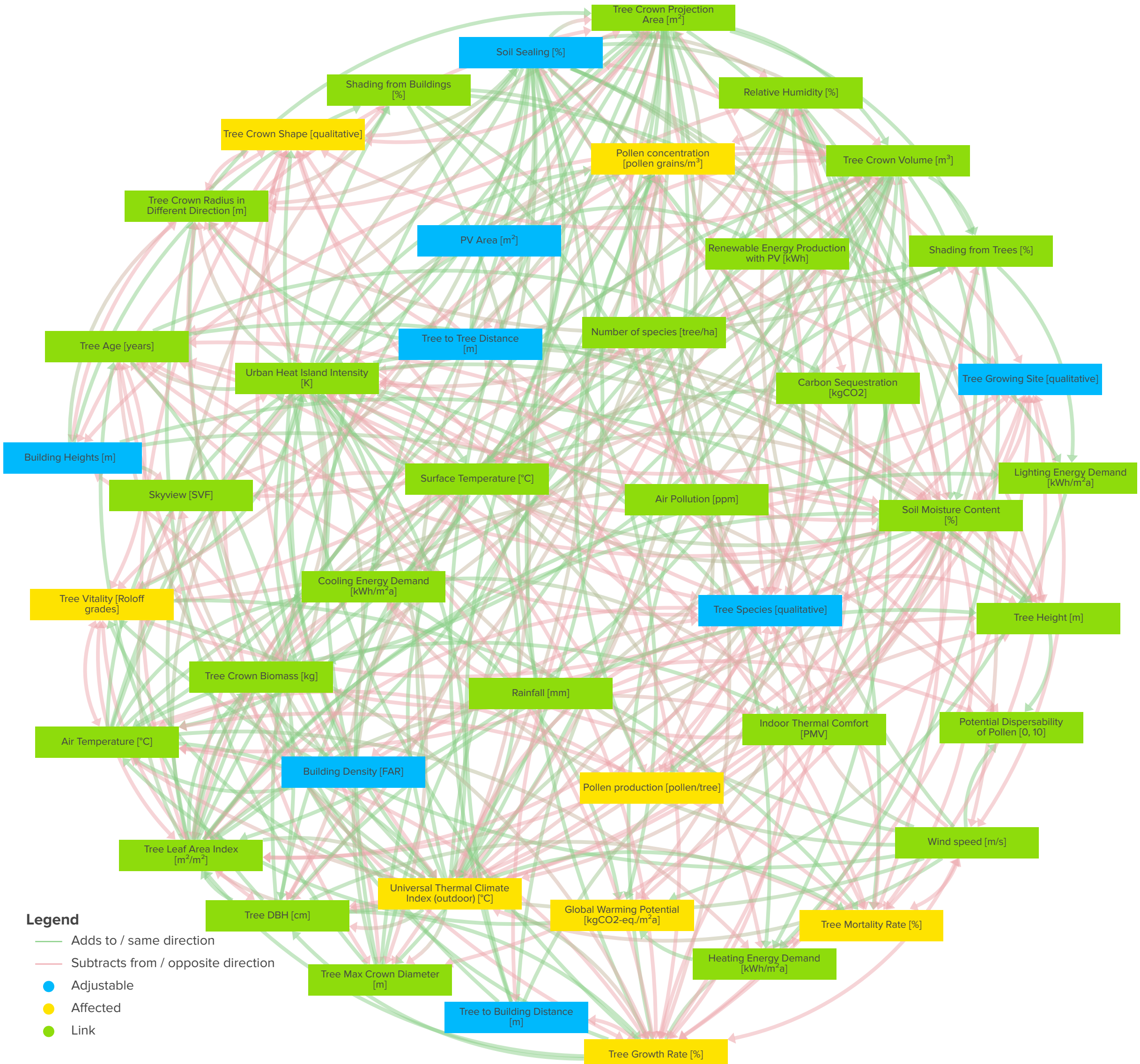

Figure 6. Causal-loop diagram combined from all indicators. For better readability click here.

4.4. Formulating hypotheses on connections

In this section, we present how the developed causal-loop diagram helps formulate hypotheses about the connection of indicators. While some relationships seem obvious, several indirect relationships between indicators remain to be described and uncovered in future research. Constructing hypotheses regarding these relationships and interdependencies enables researchers to focus on testing and validating these connections through empirical evidence. This contributes to understanding systemic behavior in the green-grey system described here.

4.4.1. Building Density influences Tree Growth Rate

By examining the causal-loop relationship between two arbitrary indicators, namely *Tree Growth Rate* and *Building Density*, we aim to elucidate how this causal-loop can formulate connecting hypotheses. In Figure 7, we present the refined causal-loop involving two primary indicators

(*Tree Growth Rate* and *Building Density*) and four pivotal connecting indicators (*Soil Sealing*, *Urban Heat Island Intensity*, *Soil Moisture Content*, and *Air Temperature*). It becomes readily apparent that *Building Density* exerts a positive and direct influence (+ +) on *Soil Sealing*, *UHI Intensity*, and *Air Temperature*. However, the effect of *Building Density* on *Tree Growth Rate* is more nuanced. While it does establish relationships with the other indicators, whether these effects are positive (+ +) or adverse (+ −) remains unclear. Among the various indirect and interconnected pathways from *Building Density* to *Tree Growth Rate*, only the path through *Soil Sealing* is not mutual. It negatively impacts (+ −) tree growth as *Soil Sealing* increases. To predict the impact of *Building Density* on *Tree Growth Rate*, it is imperative to consider not only the more apparent indicators, such as *Soil Sealing* and *Air Temperature*, but also the additional factors like *Urban Heat Island Intensity* and *Soil Moisture Content*. Franceschi et al. [61] necessitate this expansion in consideration, which demonstrates how the local environment can significantly influence *Tree Growth* and *Crown Shape*.

Our hypothesis posits that *Building Density* has a generally adverse effect (+ −) on *Tree Growth Rate*; an increase in *Building Density* will correspond to a decrease in the average *Tree Growth Rate*.

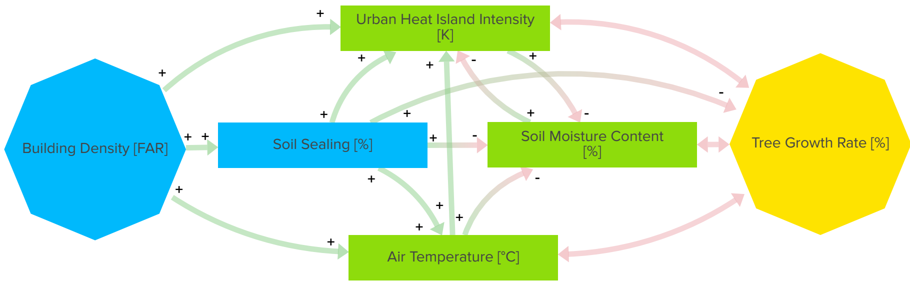

Figure 7. Filtered causal-loop diagram for formulating a hypothesis on the connection of *Building Density* and *Tree Growth Rate*.

4.4.2. *Tree to Tree Distance influences Pollen Concentration*

Another hypothesis is formulated with the indicators *Tree to Tree Distance* and *Pollen Concentration*. Figure 10 shows the isolated connection between the two indicators. *Tree to Tree Distance* exerts either a direct influence, in the case of *Tree Crown Volume*, or an indirect influence, in the case of *Tree Crown Projection Area* and *Tree Growth Rate*, on the indicator *Pollen Concentration* [42]. However, the influence of *Tree to Tree Distance* is not directly determinable for the other indicators apart from a direct positive influence (+ +) on *Tree Crown Projection*. *Tree Crown Volume* can be taken as an indicator of *Pollen Concentration* since, according to [90], it is an effective tool for pollen forecasting, which is also evident from the causal-loop diagram. Likewise, *Tree Crown Volume* is positive related (+ +) to the *LAI*. This is determined with a mutual connection by the *Tree Species* and the *Number of Species*, which also influences the *Pollen Concentration*. The *LAI* is positively influenced (+ +) by all three indicators that are directly influenced by *Tree to Tree Distance* (*Tree Growth Rate*, *Tree Crown Projection*and *Tree Crown Volume*). This demonstrates that indicators without direct influence on *Pollen Concentration* can indeed influence it in the system and would not have been visible without a causal-loop. For example, *Tree Growth Rate* has no direct influence on *Pollen Concentration*, but it does on *Tree Crown Projection Area* (+ +), *Tree Crown Volume* (+ +), and *LAI* (+ +). Likewise, *Pollen Concentration* is directly affected by *Air Temperature* (+ +), *Wind Speed* (+ −), *Relative Humidity* (+ −), and tree species parameters, which have an indeterminate connection (+ −) with *Tree Growth Rate*. Therefore, to determine the effect of *Tree to Tree Distance* on *Pollen Concentration*, it is necessary to consider not only the obvious indicator *Tree Crown Volume* which has a mutual connection (+ −), but also *Tree Growth Rate*, *Tree Crown Projection Area* and, related indicators.

We hypothesize that *Tree to Tree Distance* influences the *Pollen Concentration*. However, the direction of influence varies depending on conditions and should therefore be investigated individually for each study area and *Tree Species*.

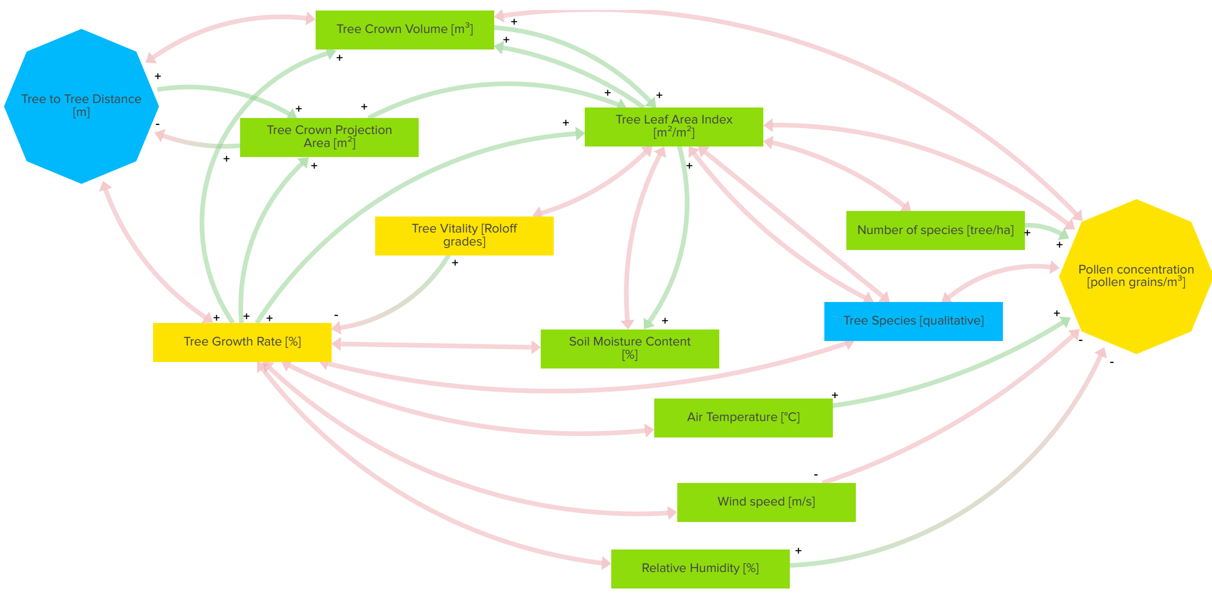

Figure 8. Filtered causal-loop diagram for formulating a hypothesis on the connection of *Tree to Tree Distance* and *Pollen Concentration*.

5. Conclusion and outlook

In this report, we applied a systems thinking approach to develop a causal-loop diagram that captures the interactions between buildings and UGI. We used literature and expert talks to collect relevant interactions and brought them together for the main indicators of the green-grey nexus. Assembling these subsystems led to a final causal-loop diagram. This diagram allows us to enhance the understanding of the urban environment's systemic behavior and to derive new research hypotheses. During the creation of the diagram, it became clear that the approach is not only justified by the final outcome. The iterative model-building process improved our understanding of the challenges arising from systemic behavior in the urban fabric. Eppinger et al. quote on this [91]:

"Tremendous value can come from the discoveries made during the building of a process model regardless of any further value derived from analyzing the model."

We know that the causal-loop diagram developed in this paper is incomplete and represents only a base for future work. Nevertheless, it was valuable for our intention of developing a profound system model for the urban environment.

After this general conclusion on how iterative system modeling can improve the understanding of the urban fabric, we conclude from the results presented in section 4. Urban form and green infrastructure emerged as two key linking variables between indoor and outdoor spaces. Their coordination with each other during planning processes should be pushed in urban planning and advanced in research. Most connections in the causal-loop diagram refer to affected or linking variables. The adjustable indicators showed few linkages, so their systemic impact was initially hard to grasp. Instead, one must understand the existing linkages that form the overall impact on the affected variables. This underscores the need for planners to be aware of the interactions their adjustments may cause within this system to determine the impact and to avoid trade-offs.

Formulating hypotheses has shown that indirect relationships can be found between almost any two indicators. However, assessing their relevance is a challenging task. Therefore, further research on the strength of the connections is needed. Nevertheless, understanding this large number of interactions is crucial for urban planners. They must be aware of their multiple options to positively influence urban aspects. Very often, there is not just one solution to challenges but several. Hence, a system model of the urban fabric supports planners in understanding possible synergies and trade-offs that come with their design decisions. Solutions may be ideally suited to achieve some goals, but if they harm others, this will increase costs to keep a neighborhood and its ecosystems vital. Research gives several examples where vegetation harms carbon emissions but improves heat mitigation [92]. By evaluating the causal-loop diagram developed in this study, we can confirm our initial hypothesis that indicators related to UGI are highly connected to the energy demand of buildings, human comfort, and health.

We identified several points for diving deeper into the holistic modeling of the urban system as demanded in the SETS framework. The two exemplary hypotheses should be subjected to empirical testing. This will determine the validity of the connections formulated for argumentation and their significance for the whole system. Additionally, assigning weights to the strength of these connections would further enhance holistic understanding. There are still some connections for which we couldn't determine whether they are directed positive or negative. Enhancing the model with simulation or regression-based connections would contribute to developing a quantifiable approach. We expect this step to also improve the determination of essential connections. Our causal-loop diagram is well suited for this next step, as we used only quantifiable indicators.

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