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# Dynamic and Heterogeneity of Urban Heat Island: A Theoretical Framework in the Context of Urban Ecology

**Zahra Mokhtari [1,†], Shahindokht Barghjelveh [1,†], Romina Sayahnia [1], Salman Qureshi [2] and Alessio Russo [3,*]**

1 Department of Environmental Planning and Design, Environmental Sciences Research Institute, Shahid Beheshti University, Tehran 1983969411, Iran; z_mokhtari@sbu.ac.ir (Z.M.); s-barghjelveh@sbu.ac.ir (S.B.); r_sayahnia@sbu.ac.ir (R.S.)
2 Department of Geography, Humboldt University of Berlin, Rudower Chaussee 16, 12557 Berlin, Germany; salman.qureshi@geo.hu-berlin.de
3 School of Arts, University of Gloucestershire, Francis Close Hall Campus, Swindon Road, Cheltenham GL50 4AZ, UK
* Correspondence: arusso@glos.ac.uk
† These authors contributed equally to this work.

**Abstract:** The dynamic and heterogeneity of the urban heat island (UHI) is the result of the interactions between biotic, physical, social, and built components. Urban ecology as a transdisciplinary science can provide a context to understand the complex social–biophysical issues such as the thermal environment in cities. This study aimed at developing a theoretical framework to elucidate the interactions between the social–biophysical patterns and processes mediating UHI. To do it, we conducted a theoretical review to delineate UHI complexity using the concept of dynamic heterogeneity of pattern, process, and function in UHI phenomenon. Furthermore, a hypothetical heterogeneity spiral (i.e., driver-outcome spiral) related to the UHI was conceived as a model template. The adopted theoretical framework can provide a holistic vision of the UHI, contributing to a better understanding of UHI's spatial variations in long-term studies. Through the developed framework, we can devise appropriate methodological approaches (i.e., statistic-based techniques) to develop prediction models of UHI's spatial heterogeneity.

**Keywords:** process-based approach; transdisciplinary research; theoretical review, urban heat island mitigation; social–biophysical interaction; compositional and configurational heterogeneity

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## 1. Introduction

Urban regions consist of human and natural components that constantly change due to complex interactions within and between biophysical and social systems [1–3]. Therefore, these changes lead to the formation of unique landscapes, characterized by an extraordinary variety of land uses [4,5], which affect the surface–atmosphere energy balance and urban thermal environment (UTE) [6,7]. Dense urban settings tend to be significantly warmer than the nearby rural area which is known as urban heat island (UHI) phenomenon [8,9]. The UHI phenomenon exerts impacts on human heat-related health and comfort, particularly during heat waves [10,11]; moreover, it affects energy consumption, water quality, carbon dioxide emissions, and air pollution [12–17]. Due to health and environmental concerns, the UHI effect has aroused widespread attention in recent decades, leading to a cumulative body of research aiming to explore its drivers, formation, and consequences [18–20].

The spatial pattern of UHI is commonly retrieved from thermal data of satellite images such as Landsat 8-thermal infrared sensor (TIRS) and Moderate Resolution Imaging Spectroradiometer (MODIS) thermal infrared data, which are known as land surface temperature (LST) [21]. To capture the temperature of the heterogeneous surface (i.e, various land uses) LST within an urban landscape, unmanned aerial vehicles or drones have been introduced to retrieve LST at sub-meter spatial resolutions. The drone's spatial and temporal resolutions are highly advantageous for evaluating the variability of LST at fine spatial and temporal scales in an urban heterogeneous system [22,23].

Due to a wide diversity of socio-economic and biophysical intertwining drivers and outcomes, the UHI is a complex issue to study [13,24–28]. In addition to the complex interactions, Cadenasso et al. [29] argued that the extreme complexity of urban issues arises from the spatial attribute (i.e., configuration and composition) of urban mosaic patches and their temporal changes. Similarly, the configuration and composition attributes of urban patches (i.e., green and built-up patches) affect the thermal environment [30–34].

The science of urban ecology deals with the complex social–biophysical issues of cities [35,36] and investigates the interactions between complex biological systems, built structures, and human actions [37–39]. Considering the principle of urban ecology that ecological (biophysical) patterns and processes affect ecosystem services [39], it gives an insight into how urban ecology would be beneficial in investigating the UHI. Urban ecology as a transdisciplinary science assists society in moving toward sustainability and resilience [40–42]. It focuses on spatial-temporal patterns of urbanization and how they affect social–ecological processes and functions, ecosystem services, human wellbeing, and urban sustainability [40,43,44]. McPhearson et al. [35] argued that urban ecology provides a robust and holistic approach to the study of cities, helping the decision-makers to understand the complex relationships among social, ecological, economic, and technological systems. Therefore, developing theoretical and empirical studies related to the different issues in the context of urban ecology is essential [35]. In urban ecology, the pattern of an urban area is considered to be spatially heterogeneous and to have an influence on ecological processes [45]. These processes can be investigated by considering three broad realms: the flow of material and energy, biotic performance, and human actions [46]. UHI, as a result of social–biophysical interactions, is a spatially heterogeneous and temporally dynamic phenomenon. Then, urban ecology can give a new insight into investigating UHI.

Landscape ecology, as a holistic transdisciplinary science [47,48], explicitly emphasizes spatial composition and configuration, and its consequences on biophysical processes like biogeochemical fluxes and socio-economic processes [49–51]. Recently, urban landscape ecology [50,52] as the invention of landscape ecology and urban ecology [52], provides an appropriate context for understanding the formation, the effects of spatial and dynamical heterogeneity, and the relationship between landscape patterns (i.e., land cover/land use composition and configuration) and biophysical and socio-economic processes in multiple scales of time and space [52]. According to the urban landscape ecology, the compositional and configurational attributes like connectivity, distance from green area, shape characteristics, density, and degree of aggregation of patches exert impacts on thermal processes and land surface temperature [32,53–55].

Integrating social and ecological knowledge and data is critical to promoting the modeling of an urban ecosystem [56–60]. Therefore, to study the integrated complex infrastructural–social–ecological issues in urban ecology, different approaches and frameworks like a human ecosystem, Metacity, ecological feedback model, pattern–process–function, and dynamic heterogeneity like patch dynamic, dynamic heterogeneity, pattern–process–function, urban–rural gradient, ecosystem service framework, ecosystem service integrity, human ecosystem framework have been developed in recent years [46,56,61–63].

To study the integrated complex infrastructural–social–ecological issues in urban ecology, different approaches and frameworks like a human ecosystem, pattern–process–function, and dynamic heterogeneity [46,64,65], which basically include similar concepts, have been developing. The concept of spatial heterogeneity can be applied to urban planning and management: social–biophysical processes mediate urban functions and sustainability [66]. In other words, urban ecology as transdisciplinary research integrates human actions and perceptions and policymaking with biophysical components [35,42,58,67–73]. For instance, residents may respond to the heat in different ways like tree planting or using air conditioners [68], meaning that decision-making and human actions affect biophysical processes that change the UHI. When exploring the mechanisms behind complex urban phenomena, the process-based 'dynamic heterogeneity' approach can help clarify the interactions between human and biophysical components [35,68].

A framework in urban ecology refers to intertwined mechanisms or processes which can be tested using various hypotheses [40,74]. Synthesizing conceptual frameworks is essential in advancing urban ecology towards a strong science of cities [35]. The magnitude of interactions is regulated by policy, governance, culture, and individual behavior of the urban system of the urban system [75]. Integrating human actions into the urban ecosystem is widely perceived at the conceptual level, but developing effective and integrative theories and their applications in an urban system study still remains a challenge [76,77].

A dynamic heterogeneity approach is a useful tool for enhancing ecological integration and exploring the interactions between social and biophysical patterns and processes in urban ecosystems [46]. Understanding the complex interactions between processes, identifying their driving factors, and, ultimately, predicting the behaviour of environmental systems are among the main objectives of environmental research [78]. It can be inferred that the concept of dynamic heterogeneity can be applied to long-term research, facilitating the integration of ecosystem components and the development of predictive models [46].

Although there are a large number of systematic reviews related to the different aspects of the UHI phenomenon [79–81], it has not been investigated using a "theoretical review" lying in urban ecology. For instance, Deilami et al. [79] organized a synthesis review to identify the spatio-temporal factors and their causal mechanisms or processes that mitigate the UHI effect. Considering all the above, we aimed to develop a theoretical framework for a better understanding of the social–biophysical mechanisms behind UHIs' heterogeneity through time. In this article, we conducted a theoretical review to illuminate how the social–biological–physical processes contribute to forming the UHI in an urban ecosystem and consequently cause the dynamic and heterogeneity of UHI. To achieve the goal, we made two main implementations: (1) the dynamic heterogeneity approach was adjusted to the UHIs' dynamics and heterogeneity and (2) a template model of the driver–outcome spiral (i.e., heterogeneity spiral) was conceived for the UHI phenomenon. The proposed conceptual framework offers a comprehensive perspective of the UHI phenomenon in the context of urban ecology, supporting the analysis of UHIs' spatial heterogeneity in long-term studies.

## 2. Method

In this article, we conducted a theoretical review [82,83] in regard to the concept of "dynamic heterogeneity" lying in the urban ecology context. A theoretical review consists of concepts, together with their definitions, and existing theories that were used for UHI study. A theoretical review is drawn based on the existing conceptual and empirical studies to provide a higher level of understanding of various concepts and relationships in the studied topic [83]. In this review, we attempted to demonstrate an understanding of theories and concepts that are relevant to the UHI. In fact, in this research, we saw the UHI phenomenon from the aspect of the dynamic heterogeneity framework which itself is an inclusive framework and includes many interrelated concepts.

Since the basic idea of the research originated from the "dynamic heterogeneity" approach, firstly, it was necessary to define the concept of dynamic and heterogeneity in urban ecosystems. In the first section of the paper, we reviewed the principles of urban ecology in order to elucidate the UHI. The second section reviewed papers that primarily consisted of specific variables related to the dynamics and heterogeneity of the UHI. The authors organized the papers according to whether they focused on the social, biological, or physical attributes that affect the dynamics and heterogeneity of the UHI. In the final section, a hypothetical spiral of dynamic heterogeneity of UHI was created based on empirical evidence of UHI studies. Following an initial search, the abstract and the content of the articles identified by the search engines were reviewed. The number of articles containing the keywords was extremely broad, and in many cases, the concepts that we sought were not recognizable only through keywords and titles. Therefore, the articles were screened and those which did not match our goals were excluded.

The literature review was based on searching peer-reviewed articles in search engines of ISI Web of Science and Scopus. To synthesize the literature, we used a broad range of keywords from diverse disciplines to identify papers related to our questions: What are the reciprocal interactions between physical and biological processes in the UHI phenomenon? What are the reciprocal interactions between physical and human processes in the UHI phenomenon? What are the reciprocal interactions between human and biological processes in the UHI phenomenon? For each process realm, we identified several variables, for instance, for the social process, we used human health, human comfort, energy consumption, household income, decision-making, and mitigation policy. These terms were chosen based on our knowledge acquired from basic literature. The keywords represented in Table 1 was related to the concepts of urban ecology and biological, physical, social, economic, and built variables that exert an influence on the dynamics and heterogeneity of the UHI.

**Table 1.** The basic query for paper selection by keywords in concepts of urban ecology and UHI.

| Concepts of "Urban Ecology" | Keywords in UHI Literature |
|---|---|
| Urban ecosystem | "Urbanization" OR "Urban development" OR "UHI" OR |
| Social–biophysical (ecological) interaction | "cold spot and hot spot" OR "land surface temperature" |
| Pattern–process | OR "Spatial-temporal change" OR "Human intervention" |
| Dynamic and Heterogeneity | OR "mitigation policy" OR "tree protection policy" OR |
| Spatial heterogeneity | "climate regulation" or "cooling effect" OR "decision-mak- |
| Social–ecological dynamic | ing" OR "artificial heat production" OR "human health" |
| | OR "energy consumption" OR "anthropogenic heat |
| | sources" OR "land architecture" OR "tree diversity" OR |
| Biophysical dynamic | "tree attribute" OR "urban forest" OR "energy and water |
| | flow" OR "heat wave" OR "wind direction" OR "urban |
| | green space" OR "cooling effect" |
| Complexity | |
| Cause and effect | |

## 3. Dynamic and Heterogeneity in Urban Ecosystems

In studying urban phenomena, understanding the causes and consequences of spatial heterogeneity of patterns, processes, and functions are considered critical issues [46,84]. Pickett et al. [46] developed the dynamic heterogeneity approach as an inclusive theory, which provides a framework to explore the mechanisms, outcomes, and drivers of spatial variability over time. In the urban scientific literature, the term 'dynamic' indicates how a patch or patch mosaic changes structurally and functionally through time [85], while 'heterogeneity' refers to the spatial variation of a property of interest across a landscape [86]. In particular, 'spatial heterogeneity' refers to the causal structure and spatial variability of a specified object [40,74].

However, Pickett et al. [46] argued that 'heterogeneity' is not just about the patterns, but also the social–biophysical processes which are spatially heterogeneous. It means that heterogeneity is an outcome of past social and biophysical processes, and can act as a driver of future social and biophysical processes (i.e., heterogeneity observed at a certain time is the result of prior conditions). Therefore, by analyzing heterogeneity within different time intervals, it is possible to conduct long-term research in the urban ecosystem [46,87].

The urban dynamic heterogeneity approach could help recognize the interactions between social and biophysical components. Human ecosystems consist of heterogeneous biological, physical, social, and infrastructural components—the heterogeneous layers interact with each other at different scales. Over time, these interactions create a new type of heterogeneity. Since there are potential interactions between all the components, the aim of the research determines which interactions should be investigated at a particular scale. The concept of the human ecosystem emphasizes how heterogeneity of human interventions influences heterogeneity of buildings and infrastructures; moreover, social and biophysical attributes and fluxes outside urban boundaries have been found to affect heterogeneity over time [46].

According to landscape ecology, patterns are defined as spatial attributes of a landscape: they encompass both the composition and configuration of patches and influence biophysical processes [84]. Therefore, pattern heterogeneity can be explained by both compositional and configurational heterogeneities [88]. In an urban ecosystem, the process refers to the transferring of energy, material, or organisms, flux, and cycling of elements within a city [65], which are inherently heterogeneous in space and occur in particular places on a landscape [89,90]. In an urban ecosystem, patterns and processes interact reciprocally and are theoretically inseparable (i.e., there is a coupling of patterns and processes) [65,79,91,92]. The function is the interaction between pattern and processes that supports delivering ecosystem services like climate regulation in urban areas [65]. In a time frame, pattern heterogeneity leads to process and functional heterogeneity [46]. Functional heterogeneity is defined as the spatial variation of the urban ecosystem's capacity to provide services [65].

Urban ecologists hypothesized that the interaction between social–biophysical patterns and processes can be observed in the form of surface cover or land use/land cover (LULC). LULC is regarded as an ecological indicator in urban studies. It affects ecological patterns and processes, causing broad environmental phenomena like the UHI. The new biophysical conditions such as UHI affects human attitudes which may lead to the establishment of new policies. These policies themselves change the LULC over time [2,93].

Pickett et al. [46] outlined the existence of three interactive processes that lead to the hybridization of biophysical, social, and built components of the human ecosystem. These processes include (1) flows of material and energy (e.g., heat fluxes); (2) biological potentials or biotic performances (e.g., spatial arrangement of organisms, their traits, and community dynamics); (3) human actions and interventions and decision-making in an urban ecosystem.

The vast realm of material and energy flow in the urban ecosystem refers to the transforming and transferring of food, goods, and fuel. In other words, they can be defined by the pathways as the input and output of water, food, air, fuel, and heat [94–96]. The resources that stream into cities shape and modify the structure of the urban biological system, empower, and drive urban capacities with an impact on common biological forms of cities, and in the long run, create yields that remain inside the boundary or are sent out beyond the boundary [97]. Biotic differentiation (biota differentiation) is defined as various biodiversity (fauna and flora) and species richness within an ecosystem [98,99]. Regarding the social or human-made process, it involves social–economic attributes like zoning regulation, lifestyle and livelihood arrangement, economic and political policy, neighborhood identity, housing price, the pattern of investment, access to the road and green area, house density, population distribution, the market economy, general patterns of income, and access to the service which make social–economic heterogeneity across the city [100–104]. Table 2 represents the main attributes of the urban ecosystem to illuminate dynamics and heterogeneity.

**Table 2.** The main attributes associated with h dynamic heterogeneity approach to elucidate UHI in an urban ecosystem (adapted from Pickett et al. [46]).

- Urban systems are extraordinarily heterogeneous.
- Heterogeneity encompasses space and time, patterns, and processes.
- There are different layers of biophysical, social, and infrastructural heterogeneity.
- The layers of heterogeneity interact with each other at different scales.
- Heterogeneity acts both as driver and outcome, so mediates between the social and biophysical components in the urban system.
- The interactions of different heterogeneous layers create new heterogeneities.
- Social and biophysical fluxes outside the urban boundary affect heterogeneity through time.
- Heterogeneity affects urban functions that lead to ecosystem services delivery, human wellbeing, and sustainability.
- Human beings' feedback amplify dynamic heterogeneity in urban systems.

## 4. Dynamic and Heterogeneity of UHI

In urban ecology, the human ecosystem consists of interacting biotic, physical, social, and built components that are temporally dynamic and spatially heterogeneous [46]. In association with UHI investigation, there are manifold types of biotic, physical, social, and built heterogeneities that mediate the spatial variation of UHI (Figure 1). There is a multitude of variables to study the biotic, physical, social, and built components that contribute to the UHI spatial heterogeneity. The arrows show the potential interactions between the heterogeneous components. The interactions between the components can be determined by the aim of particular research. Biotic heterogeneity can be defined as the heterogeneous distribution of natural and semi-natural patches (including forests, woodland, shrubs, green areas, and wetlands) across a city, which affect differentially the land surface temperature [55,105–109]. In particular, heterogeneity of vegetation distribution, abundance, and tree species can affect the temperature in various ways, such as providing shade, modifying the landscape's thermal properties (i.e., albedo and emissivity modification), altering the air movement, and heat exchange (i.e., wind blowing) through evapotranspiration [13,109–117]. The effect of biological differentiation on the thermal environment and the UHI phenomenon can be assessed using vegetation indices, like the greenness index and the normalized difference vegetation index (NDVI) [118–120].

Physical heterogeneity derives can be ascertained by topographic features (i.e., physical layers) like elevation, aspect, and slope. These features affect the thermal environment and control the UHI phenomenon [25,121,122]. Heterogeneous patterns of topographic attributes in an urban region alter the potential radiation and thermal loads (i.e., alter the energy flow process) [121].

In terms of the built component in the context of an urban ecosystem, it refers to a man-made built-up area characterized by infrastructural and technological components, changing through time due to human decision-making [46]. Notably, the characteristics of the built complex influence urban temperature and the formation of UHI. The height of buildings and their variability, as well as the spacing between buildings, affect air circulation, wind flow, and thermal energy absorption [18,24,123–125]. More importantly, the material properties of roofs and walls significantly affect both albedo and emissivity, leading to temperature alterations [13,126]. The sky view factor (SVF) is a parameter related to urban building and measures sky visibility. A reduction of the SVF leads to an increase in solar radiation absorption and a lowering of wind speed, ultimately amplifying the UHI effect [110,123,124,127–130]. Additionally, the normalized difference built-up index (NDBI), which reflects the amount of urban built-up areas, can be used to investigate the effect of the built-up surface on the intensity of the UHI phenomenon [119].

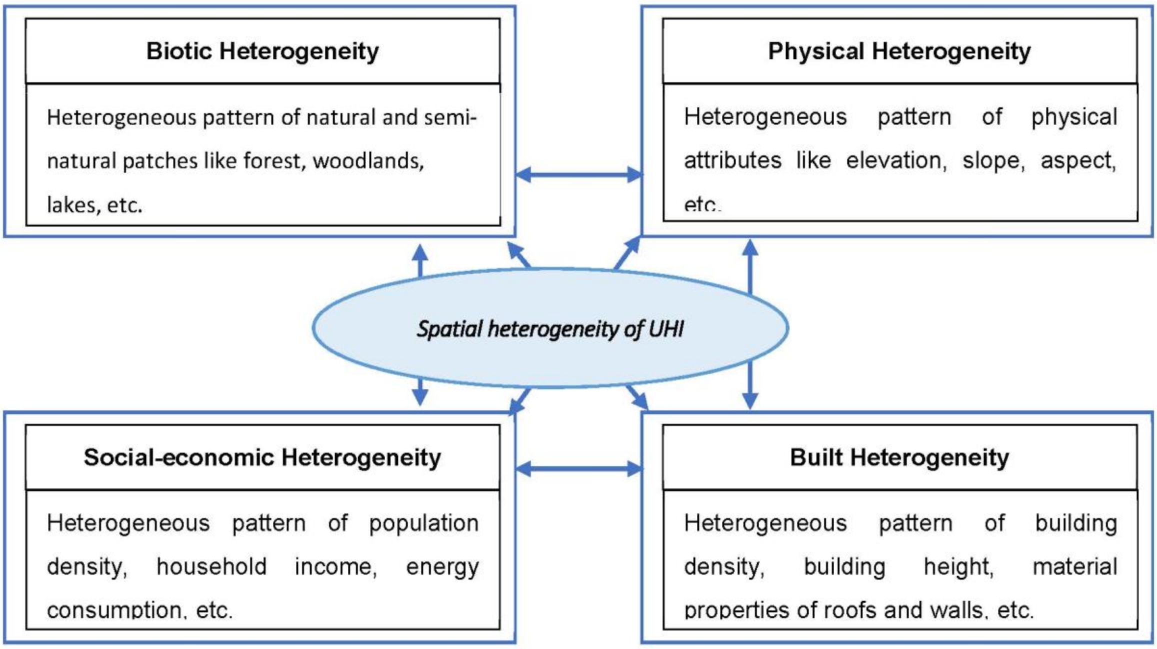


**Figure 1.** Four components of an urban ecosystem (adopted from Pickett et al. [46]) mediate the spatial heterogeneity of UHI.

Social–economic heterogeneous patterns affect urban temperatures and support the occurrence of the UHI phenomenon [25,131,132]. For instance, heterogeneities in population density and household income influence the intensity of this phenomenon [25]. Furthermore, urban anthropogenic heat emission, derived from household energy consumption and vehicular traffic, is significantly related to socio-economic activities and is considered a key factor contributing to the formation of UHI [133–135]. In this context, human perception is considered an important process capable of altering the intensity of the UHI phenomenon. For instance, there can be a tendency to plant certain species (e.g., trees that provide more shading) in neighborhoods [136–138]; moreover, people living in the hot area usually apply strategies (e.g., using air conditioning or altering the neighborhood's biophysical structure through tree planting) to mitigate the UHI effect [68]. At the same time, policymaking outcomes (e.g., increasing vegetation, constructing living (green) roofs, and promoting light-coloured surfaces) effectively influence variations of the UHIs over time [139]. The application of policies targeting the alteration of urban structures (e.g., the placement and orientation of buildings) and the residents' lifestyles can also explain temperature variations across a city [140].

The ultimate result of the reciprocal biotic–physical–social–built interactions described above mediates a spatial heterogeneous mosaic of UHI (Figure 1). This mosaic affects the biophysical–social processes (i.e., evapotranspiration, heat exchange, and decision-making processes) in urban areas (Figure 2). Each of these three processes contributing to the UHI heterogeneity is itself a large topic. The researchers can focus on each of the three processes related to the others and study the feedbacks and interactions among them. For instance, how does the decision-making process change the vegetation surface, or how energy and material flow can affect human perception.

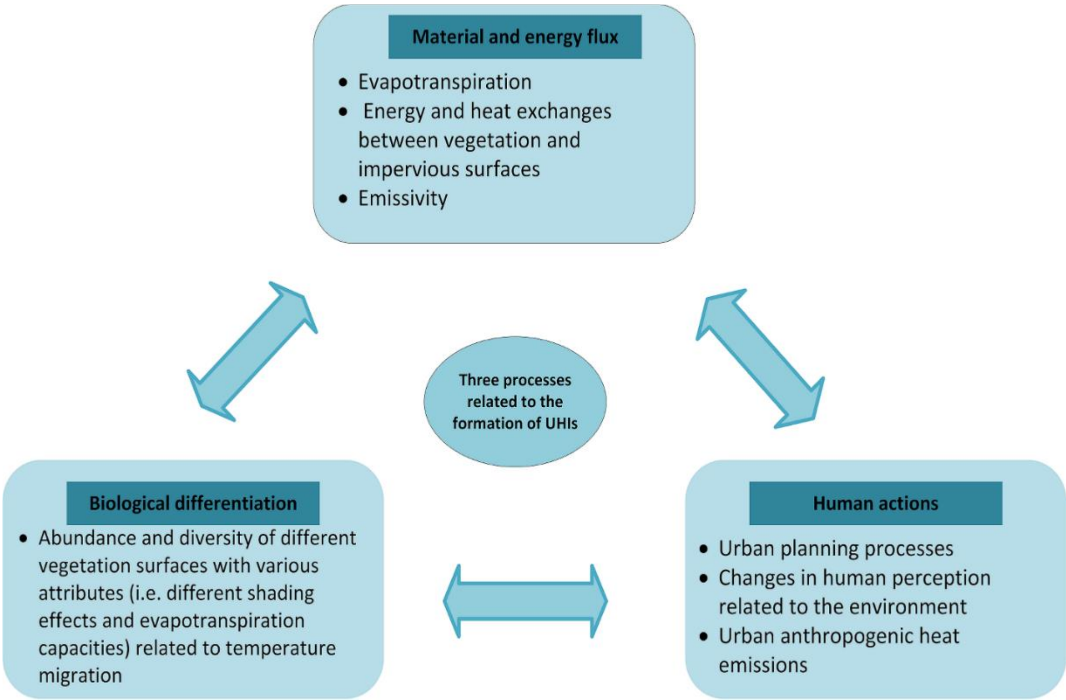


**Figure 2.** The reciprocal interaction between the processes of 'energy and material flows', 'biotic differentiation', and 'human action' (adapted from Pickett et al. [46]) contribute to the formation of UHI. For each process realm, several variables have been outlined.

Integrating Figures 1 and 2, we can adjust the dynamic heterogeneity for the case of UHI. As shown in Figure 3, the interactions between the above-mentioned coupling social–biophysical patterns and processes over time may lead to a new heterogonous UHI pattern. In other words, the interactions between the patterns and processes change the UHI heterogeneity over time which can be called "dynamic heterogeneity of UHIs". As shown in Figure 3, the interactions among a multitude of heterogeneous built–social–biophysical layers drive social–biophysical processes, and the process feedbacks change the pattern heterogeneity. The coupling interaction between heterogeneous patterns and processes can hence give birth to a new heterogeneous UHI pattern over time that is called "dynamic heterogeneity of UHI".

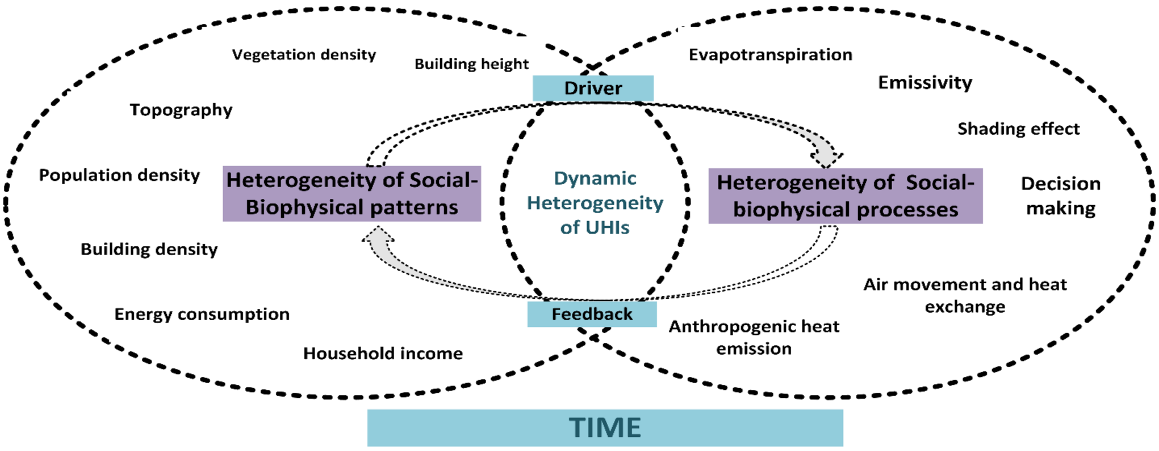


**Figure 3.** Dynamic heterogeneity approach in UHI: The interactions between four biotic–physical–social–built heterogeneous layers (variables in the left oval) make a heterogeneous pattern. The right oval shows different kinds of energy and material, biotic differentiation, and human action processes that interact reciprocally.

## 5. Driver–Outcome Spiral of UHI: Building a Model Template

The UHI is affected by numerous social–biophysical factors, as well as by the spatial arrangement of the LULC [25,141] and affects energy consumption, human health, water quality, and air pollution [14,142,143]. A template of heterogeneity or a spiral of dynamic heterogeneity [46] is a model template that indicates how a set of factors associated with a problem are potentially linked to each other. In addition, it represents the mechanisms, causes, effects, and interactions for a specific subject in a social–ecological system [68]. The above template, which was adopted from biological theories [64], follows the 'conditional statement' or 'if-then statements' (i.e., if A happens, then B is predicted: if a condition or relationship is verified, then certain results can be expected) [46,64].

In creating a driver–outcome spiral, due to the extremely wide diversity of the components, variables, and driver–outcome interactions involved, a myriad of templates can be developed to illustrate the causes and effects of the UHI. The choice of which template to build depends on the specific analytical goal: a large number of mechanistic spirals can be proposed by considering the various drivers and outcomes of the UHI. Figure 4 describes a simplified hypothetical driver–outcome spiral (i.e., a model template of the UHI dynamic heterogeneity), which was created based on a literature review. Here, heterogeneity is temporally dynamic and influences social–biophysical processes: physical, biological, and social–economic heterogeneities result from past interactions and are the drivers of future changes [46]. In this figure, the heterogeneous patterns of vegetation and impervious surfaces alter the land surface temperature pattern through biophysical processes (e.g., evapotranspiration and heat exchange) between time 1 and time 2. These, in turn, affect human comfort and health (between time 2 and time 3). Environmental concerns lead to the establishment of new policies for the mitigation of urban temperature. The decision-making policy process is expected to cause changes in land cover over time. Notably, the occurrence of pulse events (i.e., regional events out of the urban boundary) at a given time may affect heterogeneity at a subsequent time. Note: the starting point of the driver–outcome spiral, which encompasses intrinsic physical attributes (e.g., topography and climatic zone) and corresponds to 0, is not shown in this figure.

The assumptive spiral starts with a heterogeneous pattern of impervious and green patches, which are linked to changes in biophysical processes (e.g., evapotranspiration, shade, and heat exchange) through time (heterogeneity at time 1). The above heterogeneity led to a heterogeneous land surface temperature pattern (heterogeneity at time 2); in turn, temperature variations typically affect human thermal comfort and health (heterogeneity at time 3) [144–149]. In addition, high temperatures can trigger specific atmospheric chemistry procedures (e.g., increased ozone production, hydrocarbon, $PM_{10}$, and VOC concentrations), which lead to a worsening of air pollution [143,150]. Health and environmental issues deriving from high temperatures and air pollution may lead to changes in policies (heterogeneity at time 4), which would ultimately result in the alleviation of UHIs' effects [151]. Hence, policymaking processes would be the drivers of new land cover heterogeneities, starting a new turn of the spiral, which would continue to repeat through time [93]. Moreover, disturbances or pulsed events (e.g., heatwave) occurring outside urban regions (i.e., at a regional scale) [43,46] are expected to affect the UHI [152–154], giving rise to a new heterogeneity of the UHI in subsequent time.

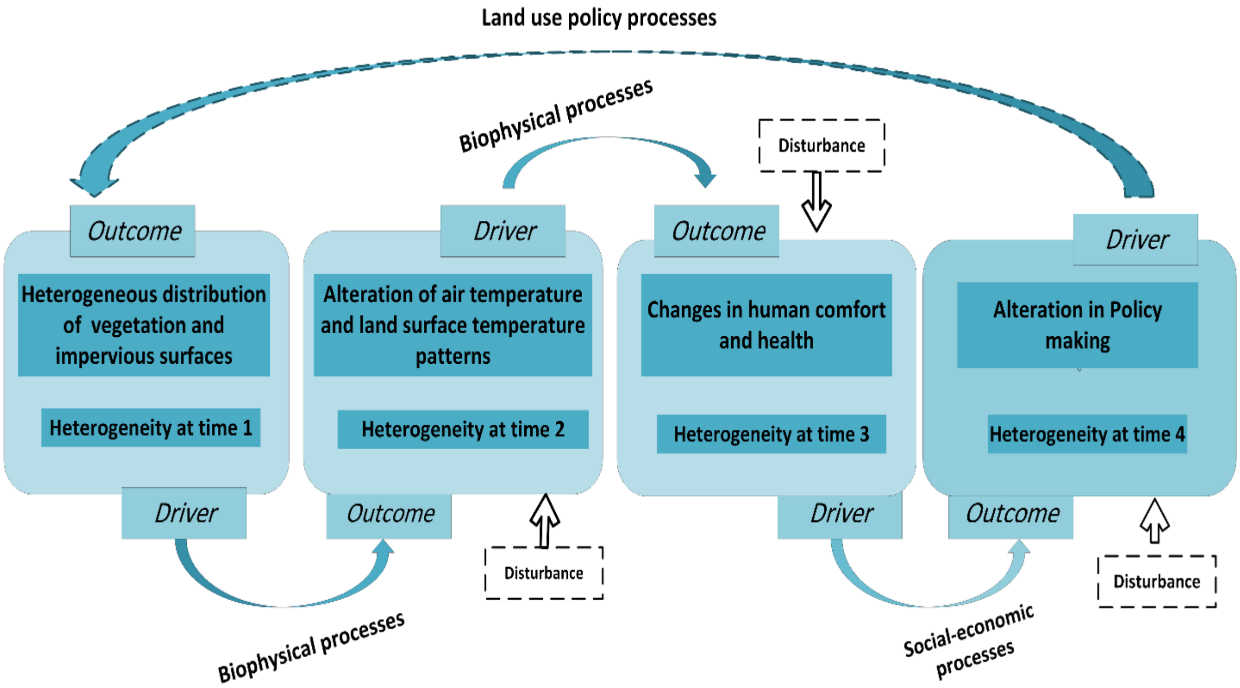


**Figure 4.** Model template: hypothetical driver–outcome spiral explaining the dynamics and heterogeneity of the UHI based on empirical evidence.

## 6. Quantifying and Modeling the Interactions and Feedback among the Processes Mediating UHI

Due to the complexity and lacking direct measurement of different social–biological–physical processes and interactions in the context of urban ecology, various approaches and statistical models have been developed to quantify the specific goal [46]. The researcher can investigate the following interactions in UHI: how biotic differentiation (e.g., forest and woodland change) may influence physical processes like solar energy flux or the wind blowing; how physical processes like heat flux affect biotic performance; how the decision-making process and human perceptions can affect biotic differentiation; how human preferences and attitudes towards particular types of plants may affect the biodiversity of the urban area that consequently change UHI intensity; how biotic attributes can change human activities or how green space and plant diversity may influence human perceptions, leading to alteration of the urban temperature. Mechanistic models can describe a complex system by bringing the components together, providing a method to test the hypotheses in holistic ways. It also can describe a phenomenon through a hypothesized or assumed mechanism/process [155,156]. This model can be applied in studying the complex issue of UHI. In addition, a Bayesian Network model is a useful tool to deal with various social–ecological processes in a specific phenomenon [157,158] and can be used in evaluating probable outcomes in complex ecological systems [159]. This approach allows for a combination of different types of data like quantitative data, expert or local knowledge, and outputs from scenario building, and can deal with lacking data, hence they are useful in areas such as ecology or social science [157]. To analyze the relationship between the unobservable variables and the observed measurement, the state-space model can also be used [160] as a flexible approach [161]. In the case of UHI, for instance, there is some unobservable variable like human perception. In this case, the researcher's knowledge from the past is needed to estimate the future change of each variable [162].

## 7. Implications of the Theoretical Framework for Urban Planning toward UHI Mitigation

The urban ecology defines the cities as complex mosaics [66], engaging numerous social, ecological, and economic issues and strategies. In addition, landscape ecology as a science for dynamic and heterogeneity study focuses on spatial patchiness [163]. A city can be planned in a way to mitigate the UHI based on the transdisciplinary science of urban ecology and landscape ecology. In urban ecology, the urban heterogeneity comprises spatial variation within the physical, natural, and technological structures [40,46]. Urban planners consider how heterogeneity changes over time as the fundamental aspect of an urban ecosystem [66]. In addition, the compositional and configurational heterogeneity also affects the UHI intensity.

Therefore, the mitigation measures lying in this theoretical framework not only focus on the biotic components but also consider a hybrid of social–biological–physical–built components. Further, it emphasizes the pattern–process–function, considering how the composition and configuration of different patches within an urban landscape change the processes and functions and consequently, alleviate urban temperature.

## 8. Conclusions

Urban ecosystems are considered thermally heterogeneous because they typically comprise many small hot and cold spots which form a spatially heterogeneous pattern [164]. When dealing with this complexity, it is hence essential to recognize the mechanisms, components, and interactions between the social–biophysical components that contribute to the creation of UHI. In this context, the holistic science of urban ecology can be appropriate for investigating urban complex issues. Urban ecology studies are generally based on custodial frameworks, which enable the integration of biophysical and social components [68]. The concepts and tools introduced by transdisciplinary urban ecology have opened new pathways to tackle urban environmental concerns and ultimately improve related planning and management activities [66].

In this study, conceptualization and delineation of the causes and effects of spatial heterogeneity are essential in urban development [46]. In the case of UHI, the literature review indicated that pattern–process–function is heterogeneous and dynamic within an urban landscape (see the previous sections). In this study, by implying dynamic heterogeneity as an underlying approach in urban ecology, we developed a theoretical framework to understand the mechanisms behind the formation of UHI. In other words, the concept of dynamic heterogeneity was adopted to UHI: the interaction between social–biophysical patterns and processes over time leads to a new heterogeneous thermal environment. Furthermore, a hypothetical 'driver–outcome' spiral (i.e., heterogeneity spiral) was set up to better understand the UHI. In creating a driver–outcome spiral, due to an excessive diversity of components, variables, and driver–outcome interactions, a myriad of templates can be developed to illustrate a spiral of heterogeneity. Building a template depends on a specific analytical goal. Pickett and colleagues outlined that an "if-then" statement or "conditional statement" (i.e., if A happens then B is predicted, can support setting up a driver–outcome hypothesis. The synthesis of the literature review in this research demonstrated that UHI, as a specific subject that lies in a human ecosystem, can be defined through the dynamic heterogeneity approach. It enables us to integrate biophysical and social processes and patterns contributing to the UHI.

However, there are limitations to responding to all the questions related to the interaction between social–biophysical processes and their impact on UHI. As many variables and their effects are not directly observable, it means that the social–ecological feedback is not well understood. So, computer programs, simulation models, and special statistical models facilitate quantitative analysis of long-term data. Further, because of excessive diversity of components and driver–outcome interactions, a myriad of templates to illustrate the dynamic heterogeneity spiral can be developed. Building the model template is dependent on the specific analytical goal.

Overall, the theoretical framework in this paper allowed the examination of UHI from an ecological point of view, demonstrating that the concept of dynamic heterogeneity can describe UHI complexity. However, there are limitations to responding to all these questions related to the interaction between processes and their impact on the social–built–biological–physical components. As many of the variables and their effects are not directly observable, then social and biophysical complexes, their feedback, and interaction are not well understood. So, computer programs, simulations, and statistical models should be used to facilitate the quantitative analysis of long-term data for sustainable urban planning. The conceptual framework can be insightful in heterogeneity management of an urban system in a way to achieve temperature mitigation and an increase of climate regulation services. According to the transdisciplinary urban ecology, in future studies, ecologists and landscape architects are urged to collaborate with city residents to mitigate the UHI effects. Moreover, potentially, the developed framework can give the insight to understand the complexity of social–biophysical phenomena like air pollution, water flow and pollution, and soil pollution toward urban sustainability.

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## References

1. McDonnell, M. Editorial: Linking and promoting research and practice in the evolving discipline of urban ecology. *J. Urban. Ecol.* **2015**, *1*-6.
2. Pauleit, S.; Breuste, J.; Qureshi, S.; Sauerwein, M. Transformation of rural-urban cultural landscapes in Europe: Integrating approaches from ecological, socio-economic and planning perspectives. *Landsc. Online* **2010**, *20*, 1–10.
3. Qureshi, S.; Haase, D.; Coles, R. The theorized urban gradient (TUG) method—A conceptual framework for socio-ecological sampling in complex urban agglomerations. *Ecol. Indic.* **2014**, *36*, 100–110.
4. Elmqvist, T.; Colding, J.; Barthel, S.; Borgström, S.; Duit, A.; Lundberg, J.; Andersson, E.; Ahrné, K.; Ernstson, H.; Folke, C.; et al. The dynamics of Social-Ecological systems in urban landscapes: Stockholm and the national urban park, Sweden. *Ann. N. Y. Acad. Sci.* **2004**, *1023*, 308–322.
5. Qureshi, S.; Haase, D. Compact, eco-, hybrid or teleconnected? Novel aspects of urban ecological research seeking compatible solutions to socio-ecological complexities. *Ecol. Indic.* **2014**, *42*, 1–5.
6. Voogt, J.A.; Oke, T.R. Thermal remote sensing of urban climates. *Remote Sens. Environ.* **2003**, *86*, 370–384.
7. Weng, Q. Thermal infrared remote sensing for urban climate and environmental studies: Methods, applications, and trends. *ISPRS J. Photogramm. Remote Sens.* **2009**, *64*, 335–344.
8. Akbari, H.; Pomerantz, M.; Taha, H. Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. *Sol. Energy* **2001**, *70*, 295–310.
9. Huang, G.; Zhou, W.; Cadenasso, M. Is everyone hot in the city? Spatial pattern of land surface temperatures, land cover and neighborhood socioeconomic characteristics in Baltimore, MD. *J. Environ. Manag.* **2011**, *92*, 1753–1759.
10. Heaviside, C.; Macintyre, H.; Vardoulakis, S. The urban heat island: Implications for health in a changing environment. *Curr. Environ. Health Rep.* **2017**, *4*, 296–305.
11. Steeneveld, G.-J.; Koopmans, S.; Heusinkveld, B.; Van Hove, L.; Holtslag, A. Quantifying urban heat island effects and human comfort for cities of variable size and urban morphology in the Netherlands. *J. Geophys. Res. Atmos.* **2011**, *116*, D20129.
12. Sun, R.; Wang, Y.; Chen, L. A distributed model for quantifying temporal-spatial patterns of anthropogenic heat based on energy consumption. *J. Clean. Product.* **2018**, *170*, 601–609.

13. Phelan, P.E.; Kaloush, K.; Miner, M.; Golden, J.; Phelan, B.; Silva III, H.; Taylor, R.A. Urban heat island: Mechanisms, implications, and possible remedies. *Annu. Rev. Environ. Resour*. **2015**, *40*, 285–307.
14. Ulpiani, G. On the linkage between urban heat island and urban pollution island: Three-decade literature review towards a conceptual framework. *Sci. Total Environ.* **2021**, *751*, 141727.
15. Romano, P.; Prataviera, E.; Carnieletto, L.; Vivian, J.; Zinzi, M.; Zarrella, A. Assessment of the urban heat island impact on building energy performance at district level with the eureca platform. *Climate* **2021**, *9*, 48.
16. Li, X.; Zhou, Y.; Yu, S.; Jia, G.; Li, H.; Li, W. Urban heat island impacts on building energy consumption: A review of approaches and findings. *Energy* **2019**, *174*, 407–419.
17. Narumi, D.; Levinson, R.; Shimoda, Y. Effect of urban heat island and global warming countermeasures on heat release and carbon dioxide emissions from a detached house. *Atmosphere* **2021**, *12*, 572.
18. Khamchiangta, D.; Dhakal, S. Physical and non-physical factors driving urban heat island: Case of Bangkok Metropolitan Administration, Thailand. *J. Environ. Manag.* **2019**, *248*, 109285.
19. Constantinescu, D.; Cheval, S.; Caracaş, G.; Dumitrescu, A. Effective monitoring and warning of Urban Heat Island effect on the indoor thermal risk in Bucharest (Romania). *Energy Build*. **2016**, *127*, 452–468.
20. Zhang, B.; Amani-Beni, M.; Shi, Y.; Xie, G. The summer microclimate of green spaces in Beijing'Olympic park and their effects on human comfort index. *Ecol. Sci.* **2018**, *37*, 77–86.
21. Avdan, U.; Jovanovska, G. Algorithm for automated mapping of land surface temperature using LANDSAT 8 satellite data. *J. Sens.* **2016**, *2016*, 1480307.
22. Gaitani, N.; Burud, I.; Thiis, T.; Santamouris, M. High-resolution spectral mapping of urban thermal properties with Unmanned Aerial Vehicles. *Build. Environ.* **2017**, *121*, 215–224.
23. Naughton, J.; McDonald, W. Evaluating the variability of urban land surface temperatures using drone observations. *Remote Sens.* **2019**, *11*, 1722.
24. Alavipanah, S.; Schreyer, J.; Haase, D.; Lakes, T.; Qureshi, S. The effect of multi-dimensional indicators on urban thermal conditions. *J. Clean. Product*. **2018**, *177*, 115–123.
25. Buyantuyev, A.; Wu, J. Urbanization diversifies land surface phenology in arid environments: Interactions among vegetation, climatic variation, and land use pattern in the Phoenix metropolitan region, USA. *Landsc. Urban Plan.* **2012**, *105*, 149–159.
26. Mirzaei, P.A. Recent challenges in modeling of urban heat island. *Sustain. Cities Soc.* **2015**, *19*, 200–206.
27. Deng, C.; Wu, C. Examining the impacts of urban biophysical compositions on surface urban heat island: A spectral unmixing and thermal mixing approach. *Remote Sens. Environ.* **2013**, *131*, 262–274.
28. Nuruzzaman, M. Urban heat island: Causes, effects and mitigation measures-a review. *Int. J. Environ. Monit. Anal.* **2015**, *3*, 67–73.
29. Cadenasso, M.; Pickett, S.; Grove, J. Dimensions of ecosystem complexity: Heterogeneity, connectivity, and history. *Ecol. Complex.* **2006**, *3*, 1–12.
30. Connors, J.P.; Galletti, C.S.; Chow, W.T. Landscape configuration and urban heat island effects: Assessing the relationship between landscape characteristics and land surface temperature in Phoenix, Arizona. *Landsc. Ecol.* **2013**, *28*, 271–283.
31. Xie, M.; Wang, Y.; Chang, Q.; Fu, M.; Ye, M. Assessment of landscape patterns affecting land surface temperature in different biophysical gradients in Shenzhen, China. *Urban Ecosyst*. **2013**, *16*, 871–886.
32. Masoudi, M.; Tan, P.Y. Multi-year comparison of the effects of spatial pattern of urban green spaces on urban land surface temperature. *Landsc. Urban Plan.* **2019**, *184*, 44–58.
33. Adulkongkaew, T.; Satapanajaru, T.; Charoenhirunyingyos, S.; Singhirunnusorn, W. Effect of land cover composition and building configuration on land surface temperature in an urban-sprawl city, case study in Bangkok Metropolitan Area, Thailand. *Heliyon* **2020**, *6*, e04485.
34. Aram, F.; García, E.H.; Solgi, E.; Mansournia, S. Urban green space cooling effect in cities. *Heliyon* **2019**, *5*, e01339.
35. McPhearson, T.; Pickett, S.T.; Grimm, N.B.; Niemelä, J.; Alberti, M.; Elmqvist, T.; Weber, C.; Haase, D.; Breuste, J.; Qureshi, S. Advancing urban ecology toward a science of cities. *BioScience* **2016**, *66*, 198–212.
36. McIntyre, N.E.; Knowles-Yánez, K.; Hope, D. Urban ecology as an interdisciplinary field: Differences in the use of "urban" between the social and natural sciences. In *Urban Ecology*; Springer: Berlin/Heidelberg, Germany, 2008; pp 49–65.
37. Barot, S.; Abbadie, L.; Auclerc, A.; Barthelemy, C.; Bérille, E.; Billet, P.; Clergeau, P.; Consalès, J.-N.; Deschamp-Cottin, M.; David, A. Urban ecology, stakeholders and the future of ecology. *Sci. Total Environ.* **2019**, *667*, 475–484.
38. Inostroza, L.; Hamstead, Z.; Spyra, M.; Qureshi, S. Beyond urban–rural dichotomies: Measuring urbanisation degrees in central European landscapes using the technomass as an explicit indicator. *Ecol. Indic.* **2019**, *96*, 466–476.
39. Forman, R.T. Urban ecology principles: Are urban ecology and natural area ecology really different? *Landsc. Ecol.* **2016**, *31*, 1653–1662.
40. Wu, J. Landscape sustainability science: Ecosystem services and human well-being in changing landscapes. *Landsc. Ecol.* **2013**, *28*, 999–1023.
41. Zhou, W.; Pickett, S.; McPhearson, T. Conceptual frameworks facilitate integration for transdisciplinary urban science. *NJP Urban Sustain.* **2021**, *1*, 1–11.
42. Pickett, S.T.; Cadenasso, M.L.; Childers, D.L.; McDonnell, M.J.; Zhou, W. Evolution and future of urban ecological science: Ecology in, of, and for the city. *Ecosyst. Health Sustain*. **2016**, *2*, e01229.
43. Grimm, N.B.; Pickett, S.T.; Hale, R.L.; Cadenasso, M.L. Does the ecological concept of disturbance have utility in urban social–ecological–technological systems? *Ecosyst. Health Sustain*. **2017**, *3*, e01255.

44. Niemelä, J. Ecology of urban green spaces: The way forward in answering major research questions. *Landsc. Urban Plan.* **2014**, *125*, 298–303.
45. Li, Y.; Li, Y.; Qureshi, S.; Kappas, M.; Hubacek, K. On the relationship between landscape ecological patterns and water quality across gradient zones of rapid urbanization in coastal China. *Ecol. Model.* **2015**, *318*, 100–108.
46. Pickett, S.; Cadenasso, M.; Rosi-Marshall, E.J.; Belt, K.T.; Groffman, P.M.; Grove, J.M.; Irwin, E.G.; Kaushal, S.S.; LaDeau, S.L.; Nilon, C.H. Dynamic heterogeneity: A framework to promote ecological integration and hypothesis generation in urban systems. *Urban Ecosyst.* **2017**, *20*, 1–14.
47. Naveh, Z. Ecosystem and landscapes–a critical comparative appraisal. *J. Landsc. Ecol.* **2010**, *3*, 64–81.
48. Ahern, J. Urban landscape sustainability and resilience: The promise and challenges of integrating ecology with urban planning and design. *Landsc. Ecol.* **2013**, *28*, 1203–1212.
49. Wu, J.; Hobbs, R. Key issues and research priorities in landscape ecology: An idiosyncratic synthesis. *Landsc. Ecol.* **2002**, *17*, 355–365.
50. Francis, R.A.; Millington, J.D.; Chadwick, M.A. *Urban Landscape Ecology: Science, Policy and Practice*; Routledge: Oxfordshire, UK, 2016.
51. Darvishi, A.; Yousefi, M.; Dinan, N.M.; Angelstam, P. Assessing levels, trade-offs and synergies of landscape services in the Iranian province of Qazvin: Towards sustainable landscapes. *Landsc. Ecol.* **2022**, *37*, 305–327.
52. Wu, J.; He, C.; Huang, G.; Yu, D. Urban landscape ecology: Past, present, and future. In *Landscape Ecology for Sustainable Environment and Culture*; Springer: Berlin/Heidelberg, Germany, 2013; pp 37–53.
53. Asgarian, A.; Amiri, B.J.; Sakieh, Y. Assessing the effect of green cover spatial patterns on urban land surface temperature using landscape metrics approach. *Urban Ecosyst.* **2015**, *18*, 209–222.
54. Mokhtari, Z.; Barghjelveh, S.; Sayahnia, R.; Karami, P.; Qureshi, S.; Russo, A. Spatial pattern of the green heat sink using patch-and network-based analysis: Implication for urban temperature alleviation. *Sustain. Cities Soc.* **2022**, *83*, 103964.
55. Estoque, R.C.; Murayama, Y.; Myint, S.W. Effects of landscape composition and pattern on land surface temperature: An urban heat island study in the megacities of Southeast Asia. *Sci. Total Environ.* **2017**, *577*, 349–359.
56. Stoll, S.; Frenzel, M.; Burkhard, B.; Adamescu, M.; Augustaitis, A.; Baeßler, C.; Bonet, F.J.; Carranza, M.L.; Cazacu, C.; Cosor, G.L. Assessment of ecosystem integrity and service gradients across Europe using the LTER Europe network. *Ecol. Model.* **2015**, *295*, 75–87.
57. Yli-Pelkonen, V.; Niemelä, J. Conservation, Linking ecological and social systems in cities: Urban planning in Finland as a case. *Biodivers. Conserv.* **2005**, *14*, 1947–1967.
58. Pickett, S.T.; Cadenasso, M.L.; Grove, J.M.; Nilon, C.H.; Pouyat, R.V.; Zipperer, W.C.; Costanza, R. Urban ecological systems: Linking terrestrial ecological, physical, and socioeconomic components of metropolitan areas. In *Urban Ecology*; Springer: Berlin/Heidelberg, Germany, 2008; pp 99–122.
59. Anderson, P.; Elmqvist, T. Urban ecological and social-ecological research in the City of Cape Town: Insights emerging from an urban ecology CityLab. *Ecol. Soc.* **2012**, *17(4)*, 23.
60. Alberti, M.; Marzluff, J.M.; Shulenberger, E.; Bradley, G.; Ryan, C.; Zumbrunnen, C. Integrating humans into ecology: Opportunities and challenges for studying urban ecosystems. *BioScience* **2003**, *53*, 1169–1179.
61. Wu, J.; Levin, S.A. A patch-based spatial modeling approach: Conceptual framework and simulation scheme. *Ecol. Model.* **1997**, *101*, 325–346.
62. Müller, F.; Hoffmann-Kroll, R.; Wiggering, H. Indicating ecosystem integrity—Theoretical concepts and environmental requirements. *Ecol. Model.* **2000**, *130*, 13–23.
63. McGrath, B.; Pickett, S.T. The metacity: A conceptual framework for integrating ecology and urban design. *Challenges* **2011**, *2*, 55–72.
64. Pickett, S.T.; Kolasa, J.; Jones, C.G. *Ecological Understanding: The Nature of Theory and the Theory of Nature*; Elsevier: Amsterdam, The Netherlands, 2010.
65. Alberti, M.J. Maintaining ecological integrity and sustaining ecosystem function in urban areas. *Curr. Opin. Environ. Sustain.* **2010**, *2*, 178-184.
66. Zhou, W.; Pickett, S.T.; Cadenasso, M.L. Shifting concepts of urban spatial heterogeneity and their implications for sustainability. *Landsc. Ecol.* **2017**, *32*, 15–30.
67. Childers, D.L.; Cadenasso, M.L.; Grove, J.M.; Marshall, V.; McGrath, B.; Pickett, S.T. An ecology for cities: A transformational nexus of design and ecology to advance climate change resilience and urban sustainability. *Sustainability* **2015**, *7*, 3774–3791.
68. Rademacher, A.; Cadenasso, M.L.; Pickett, S.T. From feedbacks to coproduction: Toward an integrated conceptual framework for urban ecosystems. *Urban Ecosyst.* **2019**, *22*, 65–76.
69. Guerrero, A.M.; Bennett, N.J.; Wilson, K.A.; Carter, N.; Gill, D.; Mills, M.; Ives, C.D.; Selinske, M.J.; Larrosa, C.; Bekessy, S. Achieving the promise of integration in social-ecological research. *Ecol. Soc.* **2018**, *23*, 28.
70. McPhearson, T.; Haase, D.; Kabisch, N.; Gren, Å. Advancing Understanding of the Complex Nature of Urban Systems. *Ecol. Indic.* **2016**, *70*, 566–573.
71. Alberti, M. *Advances in Urban Ecology: Integrating Humans and Ecological Processes in Urban Ecosystems*; Springer: Berlin/Heidelberg, Germany, 2008.
72. Andersson, E.; Haase, D.; Anderson, P.; Cortinovis, C.; Goodness, J.; Kendal, D.; Lausch, A.; McPhearson, T.; Sikorska, D.; Wellmann, T. What are the traits of a social-ecological system: Towards a framework in support of urban sustainability. *NPJ Urban Sustain.* **2021**, *1*, 1–8.
73. Tress, G.; Tress, B.; Fry, G. Clarifying integrative research concepts in landscape ecology. *Landsc. Ecol*. **2005**, *20*, 479–493.

74. Pickett, S.T.; Cadenasso, M.L.; Baker, M.E.; Band, L.E.; Boone, C.G.; Buckley, G.L.; Groffman, P.M.; Grove, J.M.; Irwin, E.G.; Kaushal, S.S. Theoretical perspectives of the baltimore ecosystem study: Conceptual evolution in a social-ecological research project. *BioScience* **2020**, *70*, 297–314.
75. Bai, X.; Surveyer, A.; Elmqvist, T.; Gatzweiler, F.W.; Güneralp, B.; Parnell, S.; Prieur-Richard, A.-H.; Shrivastava, P.; Siri, J.G.; Stafford-Smith, M. Defining and advancing a systems approach for sustainable cities. *Curr. Opin. Environ. Sustain.* **2016**, *23*, 69–78.
76. Collins, J.P.; Kinzig, A.; Grimm, N.B.; Fagan, W.F.; Hope, D.; Wu, J.; Borer, E.T. A new urban ecology: Modeling human communities as integral parts of ecosystems poses special problems for the development and testing of ecological theory. *Am. Sci.* **2000**, *88*, 416–425.
77. Coelho, D.; Ruth, M. Seeking a unified urban systems theory. *WIT Trans. Ecol. Environ.* **2006**, *93*, 179–188.
78. Schröder, B. Pattern, process, and function in landscape ecology and catchment hydrology—How can quantitative landscape ecology support predictions in ungauged basins? *Hydrol. Earth Syst. Sci.* **2006**, *10*, 967–979.
79. Deilami, K.; Kamruzzaman, M.; Liu, Y. Urban heat island effect: A systematic review of spatio-temporal factors, data, methods, and mitigation measures. *Int. J. Appl. Earth Observ. Geoinform.* **2018**, *67*, 30–42.
80. Jamei, E.; Rajagopalan, P.; Seyedmahmoudian, M.; Jamei, Y. Review on the impact of urban geometry and pedestrian level greening on outdoor thermal comfort. *Renew. Sustain. Energy Rev.* **2016**, *54*, 1002–1017.
81. Santamouris, M. Cooling the cities—A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. *Sol. Energy* **2014**, *103*, 682–703.
82. Kennedy, M.M. Defining a literature. *Educ. Res.* **2007**, *36*, 139–147.
83. Paré, G.; Trudel, M.-C.; Jaana, M.; Kitsiou, S. Synthesizing information systems knowledge: A typology of literature reviews. *Inf. Manag.* **2015**, *52*, 183–199.
84. Turner, M.G.; Chapin, F.S. Causes and consequences of spatial heterogeneity in ecosystem function. In *Ecosystem Function in Heterogeneous Landscapes*; Springer: Berlin/Heidelberg, Germany, 2005; pp. 9–30.
85. Zipperer, W.C.; Wu, J.; Pouyat, R.V.; Pickett, S.T. The application of ecological principles to urban and urbanizing landscapes. *Ecol. Appl.* **2000**, *10*, 685–688.
86. Lovett, G.M.; Jones, C.G.; Turner, M.G.; Weathers, K.C. Ecosystem function in heterogeneous landscapes. In *Ecosystem Function in Heterogeneous Landscapes*; Springer: Berlin/Heidelberg, Germany, 2005; pp. 1–4.
87. Carpenter, S.R. The need for large-scale experiments to assess and predict the response of ecosystems to perturbation. In *Successes, Limitations, and Frontiers in Ecosystem Science*; Springer: Berlin/Heidelberg, Germany, 1998; pp. 287–312.
88. Fahrig, L.; Baudry, J.; Brotons, L.; Burel, F.G.; Crist, T.O.; Fuller, R.J.; Sirami, C.; Siriwardena, G.M.; Martin, J.L. Functional landscape heterogeneity and animal biodiversity in agricultural landscapes. *Ecol. Lett.* **2011**, *14*, 101–112.
89. Turner, M.G.; Gardner, R.H.; O'neill, R.V.; O'Neill, R.V. *Landscape Ecology in Theory and Practice*; Springer: Berlin/Heidelberg, Germany, 2001; Volume 401.
90. Brown, D.G.; Aspinall, R.; Bennett, D.A. Landscape models and explanation in landscape ecology—A space for generative landscape science? *Prof. Geogr.* **2006**, *58*, 369–382.
91. Wiens, J.A.; Chr, N.; Van Horne, B.; Ims, R.A. Ecological mechanisms and landscape ecology. *Oikos* **1993**, *66*, 369–380.
92. Schröder, B.; Seppelt, R. Analysis of pattern–process interactions based on landscape models—Overview, general concepts, and methodological issues. *Ecol. Model.* **2006**, *199*, 505–516.
93. Pauleit, S.; Breuste, J.H. Land use and surface cover as urban ecological indicators. In *Handbook of Urban Ecology*; Oxford University Press: Oxford, UK, 2011.
94. Decker, E.H.; Elliott, S.; Smith, F.A.; Blake, D.R.; Rowland, F.S. Energy and material flow through the urban ecosystem. *Annu. Rev. Energy Environ.* **2000**, *25*, 685–740.
95. Zhao, W. Analysis on the characteristic of energy flow in urban ecological economic system—A case of Xiamen city. *Procedia Environ. Sci.* **2012**, *13*, 2274–2279.
96. Barles, S. Society, energy and materials: The contribution of urban metabolism studies to sustainable urban development issues. *J. Environ. Plan. Manag.* **2010**, *53*, 439–455.
97. Bai, X. Eight energy and material flow characteristics of urban ecosystems. *Ambio* **2016**, *45*, 819–830.
98. Qian, S.; Qin, D.; Wu, X.; Hu, S.; Hu, L.; Lin, D.; Zhao, L.; Shang, K.; Song, K.; Yang, Y. Urban growth and topographical factors shape patterns of spontaneous plant community diversity in a mountainous city in southwest China. *Urban For. Urban Green.* **2020**, *55*, 126814.
99. Farinha-Marques, P.; Lameiras, J.; Fernandes, C.; Silva, S.; Guilherme, F. Urban biodiversity: A review of current concepts and contributions to multidisciplinary approaches. *Innov. Eur. J. Soc. Sci. Res.* **2011**, *24*, 247–271.
100. Boone, C.G.; Fragkias, M. *Urbanization and Sustainability: Linking Urban Ecology, Environmental Justice and Global Environmental Change*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2012; Volume 3.
101. Brelsford, C.; Dumas, M.; Schlager, E.; Dermody, B.J.; Aiuvalasit, M.; Allen-Dumas, M.R.; Beecher, J.; Bhatia, U.; D'odorico, P.; Garcia, M. Developing a sustainability science approach for water systems. *Ecol. Soc.* **2020**, *25*, 1–6.
102. Irwin, E.G. New directions for urban economic models of land use change: Incorporating spatial dynamics and heterogeneity. *J. Reg. Sci.* **2010**, *50*, 65–91.
103. Feng, J.; Wu, F.; Logan, J. From homogenous to heterogeneous: The transformation of Beijing's socio-spatial structure. *Built Environ.* **2008**, *34*, 482–498.
104. Tang, M.; Li, Z.; Hu, F.; Wu, B. How does land urbanization promote urban eco-efficiency? The mediating effect of industrial structure advancement. *J. Clean. Prod.* **2020**, *272*, 122798.

105. Chun-ye, W.; Wei-ping, Z. Analysis of the impact of urban wetland on urban temperature based on remote sensing technology. *Procedia Environ. Sci.* **2011**, *10*, 1546–1552.
106. Shashua-Bar, L.; Pearlmutter, D.; Erell, E. The cooling efficiency of urban landscape strategies in a hot dry climate. *Landsc. Urban Plan.* **2009**, *92*, 179-186.
107. Sung, C.Y. Mitigating surface urban heat island by a tree protection policy: A case study of The Woodland, Texas, USA. *Urban For. Urban Green.* **2013**, *12*, 474–480.
108. Wang, W.; Zhang, B.; Zhou, W.; Lv, H.; Xiao, L.; Wang, H.; Du, H.; He, X. The effect of urbanization gradients and forest types on microclimatic regulation by trees, in association with climate, tree sizes and species compositions in Harbin city, northeastern China. *Urban Ecosyst.* **2019**, *22*, 367–384.
109. Wang, X.; Dallimer, M.; Scott, C.E.; Shi, W.; Gao, J. Tree species richness and diversity predicts the magnitude of urban heat island mitigation effects of greenspaces. *Sci. Total. Environ.* **2021**, *770*, 145211.
110. Grimmond, C.S.B.; Oke, T.R. An evapotranspiration-interception model for urban areas. *Water Resour. Res.* **1991**, *27*, 1739–1755.
111. Kjelgren, R.; Montague, T. Urban tree transpiration over turf and asphalt surfaces. *Atmos. Environ.* **1998**, *32*, 35–41.
112. Qiu, G.-Y.; LI, H.-Y.; Zhang, Q.-T.; Wan, C.; Liang, X.-J.; Li, X.-Z. Effects of evapotranspiration on mitigation of urban temperature by vegetation and urban agriculture. *J. Integr. Agric.* **2013**, *12*, 1307–1315.
113. Taha, H.; Akbari, H.; Rosenfeld, A.; Huang, J. Residential cooling loads and the urban heat island—The effects of albedo. *Build. Environ.* **1988**, *23*, 271–283.
114. Zardo, L.; Geneletti, D.; Pérez-Soba, M.; Van Eupen, M. Estimating the cooling capacity of green infrastructures to support urban planning. *Ecosyst. Serv.* **2017**, *26*, 225–235.
115. Sen, S.; Roesler, J. Wind direction and cool surface strategies on microscale urban heat island. *Urban Clim.* **2020**, *31*, 100548.
116. Schwaab, J.; Meier, R.; Mussetti, G.; Seneviratne, S.; Bürgi, C.; Davin, E.L. The role of urban trees in reducing land surface temperatures in European cities. *Nat. Commun.* **2021**, *12*, 1–11.
117. Barbierato, E.; Bernetti, I.; Capecchi, I.; Saragosa, C. Quantifying the impact of trees on land surface temperature: A downscaling algorithm at city-scale. *Eur. J. Remote Sens.* **2019**, *52* (Suppl. 4), 74–83.
118. Firozjaei, M.K.; Alavipanah, S.K.; Liu, H.; Sedighi, A.; Mijani, N.; Kiavarz, M.; Weng, Q. A PCA–OLS model for assessing the impact of surface biophysical parameters on land surface temperature variations. *Remote Sens.* **2019**, *11*, 2094.
119. Guha, S.; Govil, H.; Dey, A.; Gill, N. Analytical study of land surface temperature with NDVI and NDBI using Landsat 8 OLI and TIRS data in Florence and Naples city, Italy. *Eur. J. Remote Sens.* **2018**, *51*, 667–678.
120. Carrillo-Niquete, G.A.; Andrade, J.L.; Valdez-Lazalde, J.R.; Reyes-García, C.; Hernández-Stefanoni, J.L. Characterizing spatial and temporal deforestation and its effects on surface urban heat islands in a tropical city using Landsat time series. *Landsc. Urban Plan.* **2022**, *217*, 104280.
121. Peng, X.; Wu, W.; Zheng, Y.; Sun, J.; Hu, T.; Wang, P. Correlation analysis of land surface temperature and topographic elements in Hangzhou, China. *Sci. Rep.* **2020**, *10*, 1–16.
122. Serrano, S.V.; Prats, J.C.; Sánchez, M. Topography and Vegetation Cover Influence on Urban Heat Island of Zaragoza (Spain). In Proceedings of the 5th international conference on urban climate, Łódź, Poland, 1–5 September 2003.
123. Chun, B.; Guldmann, J.-M. Spatial statistical analysis and simulation of the urban heat island in high-density central cities. *Landsc. Urban Plan.* **2014**, *125*, 76–88.
124. Kuang, W.; Liu, Y.; Dou, Y.; Chi, W.; Chen, G.; Gao, C.; Yang, T.; Liu, J.; Zhang, R. What are hot and what are not in an urban landscape: Quantifying and explaining the land surface temperature pattern in Beijing, China. *Landsc. Ecol.* **2015**, *30*, 357–373.
125. Nassar, A.K.; Blackburn, G.A.; Whyatt, J.D. Dynamics and controls of urban heat sink and island phenomena in a desert city: Development of a local climate zone scheme using remotely-sensed inputs. *Int. J. Appl. Earth Observ. Geoinform.* **2016**, *51*, 76–90.
126. Alchapar, N.L.; Correa, E.N.; Cantón, M.A. Classification of building materials used in the urban envelopes according to their capacity for mitigation of the urban heat island in semiarid zones. *Energy Build.* **2014**, *69*, 22–32.
127. Arnfield, A.J. Two decades of urban climate research: A review of turbulence, exchanges of energy and water, and the urban heat island. *Int. J. Climatol. J. R. Meteorol. Soc.* **2003**, *23*, 1–26.
128. Arnold Jr, C.L.; Gibbons, C.J. Impervious surface coverage: The emergence of a key environmental indicator. *J. Am. Plan. Assoc.* **1996**, *62*, 243–258.
129. Gill, S.E.; Handley, J.F.; Ennos, A.R.; Pauleit, S. Adapting cities for climate change: The role of the green infrastructure. *Built Environ.* **2007**, *33*, 115–133.
130. Gunawardena, K.R.; Wells, M.J.; Kershaw, T. Utilising green and bluespace to mitigate urban heat island intensity. *Sci. Total Environ.* **2017**, *584*, 1040–1055.
131. Jenerette, G.D.; Harlan, S.L.; Brazel, A.; Jones, N.; Larsen, L.; Stefanov, W.L. Regional relationships between surface temperature, vegetation, and human settlement in a rapidly urbanizing ecosystem. *Landsc. Ecol.* **2007**, *22*, 353–365.
132. Li, Y.; Sun, Y.; Li, J.; Gao, C. Socioeconomic drivers of urban heat island effect: Empirical evidence from major Chinese cities. *Sustain. Cities Soc.* **2020**, *63*, 102425.
133. Boehme, P.; Berger, M.; Massier, T. Estimating the building based energy consumption as an anthropogenic contribution to urban heat islands. *Sustain. Cities Soc.* **2015**, *19*, 373–384.
134. Dong, Y.; Varquez, A.; Kanda, M. Global anthropogenic heat flux database with high spatial resolution. *Atmos. Environ.* **2017**, *150*, 276–294.

135. Zhu, R.; Wong, M.S.; Guilbert, É.; Chan, P.-W. Understanding heat patterns produced by vehicular flows in urban areas. *Sci. Rep.* **2017**, *7*, 1–14.
136. Avolio, M.; Pataki, D.E.; Gillespie, T.; Jenerette, G.D.; McCarthy, H.R.; Pincetl, S.; Weller-Clarke, L. Tree diversity in southern California's urban forest: The interacting roles of social and environmental variables. *Front. Ecol. Evol.* **2015**, *3*, 73.
137. Avolio, M.L.; Pataki, D.E.; Pincetl, S.; Gillespie, T.W.; Jenerette, G.D.; McCarthy, H.R. Understanding preferences for tree attributes: The relative effects of socio-economic and local environmental factors. *Urban Ecosyst.* **2015**, *18*, 73–86.
138. Morakinyo, T.E.; Ouyang, W.; Lau, K.K.-L.; Ren, C.; Ng, E. Right tree, right place (urban canyon): Tree species selection approach for optimum urban heat mitigation-development and evaluation. *Sci. Total Environ.* **2020**, *719*, 137461.
139. Rosenzweig, C.; Solecki, W.; Slosberg, R. Mitigating New York City's Heat Island with Urban Forestry, Living Roofs, and Light Surfaces. *Rep. N. Y. State Energy Res. Dev. Auth.* **2006**.
140. Yamamoto, Y. *Measures to Mitigate Urban Heat Islands*; NISTEP Science & Technology Foresight Center: Tokyo, Japan, 2006.
141. Myint, S.W.; Brazel, A.; Okin, G.; Buyantuyev, A.J.G.; Sensing, R. Combined effects of impervious surface and vegetation cover on air temperature variations in a rapidly expanding desert city. *GISci. Remote Sens.* **2010**, *47*, 301–320.
142. Sarrat, C.; Lemonsu, A.; Masson, V.; Guédalia, D. Impact of urban heat island on regional atmospheric pollution. *Atmos. Environ.* **2006**, *40*, 1743–1758.
143. Li, H.; Meier, F.; Lee, X.; Chakraborty, T.; Liu, J.; Schaap, M.; Sodoudi, S. Interaction between urban heat island and urban pollution island during summer in Berlin. *Sci. Total. Environ.* **2018**, *636*, 818–828.
144. Patz, J.A.; Campbell-Lendrum, D.; Holloway, T.; Foley, J.A. Impact of regional climate change on human health. *Nature* **2005**, *438*, 310–317.
145. Vargo, J.; Stone, B.; Habeeb, D.; Liu, P.; Russell, A. The social and spatial distribution of temperature-related health impacts from urban heat island reduction policies. *Environ. Sci. Policy* **2016**, *66*, 366–374.
146. Venter, Z.S.; Krog, N.H.; Barton, D.N. Linking green infrastructure to urban heat and human health risk mitigation in Oslo, Norway. *Sci. Total. Environ.* **2020**, *709*, 136193.
147. Van Hove, L.; Jacobs, C.; Heusinkveld, B.; Elbers, J.; Van Driel, B.; Holtslag, A. Temporal and spatial variability of urban heat island and thermal comfort within the Rotterdam agglomeration. *Build. Environ.* **2015**, *83*, 91–103.
148. Hiemstra, J.A.; Saaroni, H.; Amorim, J.H. The urban heat Island: Thermal comfort and the role of urban greening. In *The Urban Forest*; Springer: Berlin/Heidelberg, Germany, 2017; pp. 7–19.
149. Alvarez, I.; Quesada-Ganuza, L.; Briz, E.; Garmendia, L. Urban heat islands and thermal comfort: A case study of Zorrotzaurre island in Bilbao. *Sustainability* **2021**, *13*, 6106.
150. Elsayed, I. Mitigation of the urban heat island of the City of Kuala Lumpur. *Malaysia* **2012**, *11*, 1602–1613.
151. Bush, J.J.E.I.; Transitions, S. The role of local government greening policies in the transition towards nature-based cities. *Environ. Innov. Soc. Trans.* **2020**, *35*, 35–44.
152. Founda, D.; Santamouris, M. Synergies between Urban Heat Island and Heat Waves in Athens (Greece), during an extremely hot summer (2012). *Sci. Rep.* **2017**, *7*, 1–11.
153. Jiang, S.; Lee, X.; Wang, J.; Wang, K. Amplified urban heat islands during heat wave periods. *J. Geophys. Res. Atmos.* **2019**, *124*, 7797–7812.
154. Zhao, L.; Oppenheimer, M.; Zhu, Q.; Baldwin, J.W.; Ebi, K.L.; Bou-Zeid, E.; Guan, K.; Liu, X. Interactions between urban heat islands and heat waves. *Environ. Res. Lett.* **2018**, *13*, 034003.
155. Kelly, J.M. Mechanistic Models: An Underutilized Tool in Soil Science Research. *Soil Horiz.* **2014**, *55*, 1–2.
156. Cabral, J.S.; Valente, L.; Hartig, F. Mechanistic simulation models in macroecology and biogeography: State-of-art and prospects. *Ecography* **2017**, *40*, 267–280.
157. Kragt, M.E. *A Beginners Guide to Bayesian Network Modelling for Integrated Catchment Management*; Landscape Logic: Charlevoix, MI, USA, 2009.
158. Pollino, C.; Hart, B.T. Developing Bayesian Network Models within a Risk Assessment Framework. In Proceedings of the Integrating Sciences and Information Technologyfor Environmental Assessment and Decision Making, Barcelona, Spain, 7–10 July 2008.
159. Maxwell, P.S.; Pitt, K.A.; Olds, A.D.; Rissik, D.; Connolly, R.M. Identifying habitats at risk: Simple models can reveal complex ecosystem dynamics. *Ecol. Appl.* **2015**, *25*, 573–587.
160. Koller, D.; Friedman, N. *Probabilistic Graphical Models: Principles and Techniques*; MIT press: Cambridge, MA, USA, 2009.
161. Auger-Méthé, M.; Newman, K.; Cole, D.; Empacher, F.; Gryba, R.; King, A.A.; Leos-Barajas, V.; Mills Flemming, J.; Nielsen, A.; Petris, G. A guide to state–space modeling of ecological time series. *Ecol. Monogr.* **2021**, *91*, e01470.
162. Gelman, A.; Carlin, J.B.; Stern, H.S.; Rubin, D.B. *Bayesian Data Analysis*; Chapman and Hall/CRC: Boca Raton, FL, USA, 1995.
163. Forman, R.T. Interaction among landscape elements: A core of landscape ecology. *Perspect. Landsc. Ecol.* **1981**, 35–48.
164. Mokhtari, Z.; Barghjelveh, S.; Sayahnia, R. Heterogeneity of the thermal environment and its ecological evaluation in the urban region of Karaj. *Geogr. Environ. Sustain.* **2021**, *11*, 37–58.