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Examining ecological justice within the social-ecological-technological system of New York City, USA

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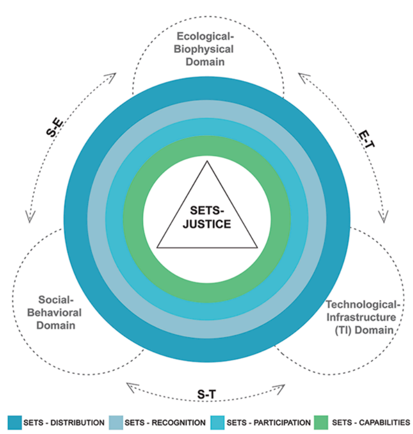
HIGHLIGHTS

- Cities are complex social-ecological-technological systems (SETS) deeply rooted with injustice.
- Ecological justice (EcJ) or justice to nature informs the SETS framework to reveal hotspots and blindspots.
- Analysis of SETS-EcJ reveals distributional inequalities, deficiencies in social-ecological recognition, participation, and capabilities.
- Nature-based solutions come to the forefront as actions to repair/restore these justice hotspots.

GRAPHICAL ABSTRACT



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ABSTRACT

Examining justice in cities requires using analytical approaches that can unpack their complex nature and reveal the many interacting dimensions that affect justice patterns and processes. Although justice in cities has been examined extensively, it has primarily focused on social and environmental dimensions. However, justice is multi-dimensional, influenced and affected by multiple actors, dynamics, and processes. In this paper we propose the use of ecological justice, as justice *of, to,* and *for* nature as a critical lens for portraying a more integral understanding of urban injustices. This lens extends the notion of justice to nature through four dimensions: distribution of harmful impacts, recognition of nature, participation of nature, and the capabilities of social-ecological systems. Through a relational lens we develop a methodology that uses the social-ecological-technological system (SETS) conceptual framework to unpack how the dimensions and interactions affect ecological justice across urban landscapes. This methodology is operationalized into measurable variables and applied through a case study in New York City. A spatial analysis of indicators that act as SETS-Justice proxies at a Community District level, reveal high spatial variability of ecological justice hotspots when looking at each dimension independently. Identifying ecological justice hotspots can provide critical information for improving ecological justice through multiple means. For example, hotspots lacking in social-ecological recognition and participation of nature can inform context-specific solutions such as policies and projects that target community engagement, capacity building, and improve ecological knowledge. Additionally, a composite analysis of SETS-Justice through the aggregation of all indicators, reveals justice hotspots different to those commonly mapped in other justice-focused studies. This approach highlights the need to jointly address issues of environmental and ecological justice.

1. Introduction

Cities are complex systems made up of social, ecological, and technological subsystems that dynamically interact, and interdependently change (Grimm et al., 2018; Markolf et al., 2018; McPhearson et al., 2016; Zhou et al., 2021). The dynamics that shape cities into places of social connection, growth and liveability, also produce devalued spaces of inequality, destruction, and fragmentation. To face these challenges, which are aggravated by climate change impacts and planetary biodiversity loss, cities require approaches that offer solutions from more holistic systems analysis. Understanding cities as complex social-ecological-technological systems (SETS) provides an integrated, multidisciplinary framework to study complex urban challenges, such as issues of urban justice and urban resilience. The social, technological, and ecological subsystems or domains in a city are shaped by the different relationships that emerge from the social-technological (S-T), social-ecological (S-E), and ecological-technological (E-T) interactions or "couplings" that can alleviate and/or reproduce complex and persistent problems (McPhearson et al., 2021). Understanding urban challenges as relational in their nature can help us get closer to achieving sustainability and resilience in cities. As a response to this relational complexity, we argue that nature-based planning and design needs to understand and consider the complexity of SETS in cities to improve urban systems' capabilities and resilience. However, this cannot be done without considering deeper issues of justice and liveability. On the grounds that justice is multidimensional and relational, we advocate for the use of ecological justice, one which explicitly includes nature and recognises issues of justice from an entangled social-ecological-technological systems lens. An ecological justice lens takes the discussion of justice from a human-centred focus, to one that recognises that an injustice committed to humans due to a displacement of environmental risks, is at its core, also an injustice committed to nature (Schlosberg, 2013; Stevis, 2000).

We propose an examination framework to identify local ecological justices/injustices and their embeddedness in SETS by presenting a conceptual SETS-Justice framework to reveal salient characteristics needed to define an ecological justice problem (Batty, 2013). By examining justice with a system's perspective, we bridge the two frameworks – SETS and ecological justice – with the premise that an integrated analysis of justice in cities can improve sustainability and resilience planning practices and programs. The common point for bridging these two conceptual frameworks lies in their relational ontologies since both conceptualize outcomes and outputs as results of interconnected, interdependent complex processes that occur in nested social-ecological-technological systems. Ecological justice's framing through four social-ecological dimensions (distribution, recognition, participation, and capabilities) seeks to expose the relationship between impacts, sources, flows, and the impacted places and spaces, the recognition of undermined and undervalued relationships, processes and actors, and the active restoration and reparation of social-ecological interactions (Schlosberg, 2012; Schlosberg, 2013; Stephens et al., 2019; Washington et al., 2018; Yaka, 2019). We build on this and extend our methodology to provide a more holistic urban systems framing through the SETS-Justice framework that recognizes the importance of technological infrastructure as an integrated driver of justice/injustice in urban (and other) systems.

Our core argument is that nature's agency, as the ability to actively shape, flourish, interact, and collaborate within its environment (Plumwood, 2001), needs to be recognised in the planning, design, and regeneration of cities. An ecological justice perspective when examined from a SETS lens advances ecological justice theory as well as enables empirical investigation of how ecological justice fits into the larger urban systems' fabric and its dynamics. Such an approach allows us to conceptually embed a justice understanding in SETS and further enrich the process ontology of SETS (Hertz et al., 2020). Empirically, such an approach will identify place-embedded injustices through a SETS-Justice framework. In this way, we articulate from a systems' perspective how ecological justice is produced and reinforced as well as identify the leverage points to inform transformative interventions for shifting to more just urban development and/or regeneration. To empirically test the analytical rigor, applicability and value of this framework, we apply it in New York City (NYC) as a case study. This allows the discussion to progress from theoretical-conceptual, to one with practical applicability in cities. Knowing where and how these injustices unfold, is the basis for preventing, mitigating, and restoring 'injustices-in-waiting' (Schaeffer Caniglia et al., 2016). 'Injustices-in-waiting' are inequalities sustained by environmental and social vulnerabilities, disparities in power and governance (Schaeffer Caniglia et al., 2016). With an empirical and place-embedded lens, we set out to uncover these injustices hidden under the surface, and make them visible, as injustices-in-place.

2. Conceptual framework: bridging SETS and ecological justice

This paper follows six methodological steps to identify SETS injustices in place (Fig. 2). In this section we develop steps 1–3, starting with positioning the theoretical grounds (step 1), followed by presenting the conceptual novelty of bridging the two frameworks (step 2), and operationalising them into indicators (step 3). In the sections that follow, we apply the SETS-Justice indicators to our case study, New York City (step 4), conduct the spatial analysis to identify injustices (step 5), and conclude with a discussion of the recommendations to address ecological injustices within the SETS interactions (step 6).

2.1. Social-ecological-technological systems (SETS)

Social-ecological-technological systems represent the diverse, complex and interconnected components made up of people, their beliefs and values, infrastructure, such as buildings, transportation and energy systems, technologies, biophysical processes, ecosystems, all the biodiversity they hold, and all the systems to manage, plan and finance these components and their interactions (Grimm et al., 2018; Grimm et al., 2015; Markolf et al., 2018; McPhearson et al., 2016; McPhearson et al., 2021). The SETS conceptual framework is represented by three subsystem domains: social-behavioural, technological-infrastructure, and ecological-biophysical (Fig. 1). The social-behavioural domain includes governance, planning and management systems, social capital (individuals, groups and networks), economic and financial systems, political systems, health and social security systems, as well as behaviours and attitudes - moral, belief, and value systems (Iwaniec et al., 2020). The technological-infrastructure domain refers to technological and infrastructure systems such as water, energy, transport, industry, food, information technology, and material/built components (Ahlborg et al., 2019; Depietri & McPhearson, 2017). The ecological-biophysical domain includes all life-supporting systems – ecosystems, biodiversity, biotic and abiotic components, and biophysical processes (Depietri & McPhearson, 2017; Iwaniec et al., 2020).

These components interact and relate with each other through the mediation, enabling, enhancing, and transforming of social-ecological-technological relationships or 'couplings' (Fig. 1). The social-ecological couplings (S-E), social-technological couplings (S-T), and ecological-technological couplings (E-T) are interactions and feedbacks between the different components of coupled systems within SETS (McPhearson et al., 2021). Social-technological couplings are complex technological, digital, and infrastructure systems created, maintained and replaced through social norms, behaviours, values, and belief systems, which are in turn shaped and evolve as they interact with technological systems (Andersson et al., 2019; Jenkins et al., 2018). Social-ecological couplings are based on the interactions and interdependencies between people and nature. These are mutually shaped through peoples' values, attitudes, behaviours, the scientific knowledge and capacity that is generated and how it is enacted through decisions and management (Zambrano et al., 2019), as well as the ecological memory which helps to carry stories and knowledge (Andersson & Barthel, 2016). Within ecological-technological couplings, technological-infrastructure systems mainly extract resources, pollute and destroy in their sources, through their flows, and in the places in which they end up as waste; as a response, hybrid green–grey approaches, based on concepts such as circular economy, industrial ecology and ecological economics, shape these processes, in which technology and infrastructure for ecosystems restoration (Andersson et al., 2019; Depietri & McPhearson, 2017). Similarly, biophysical and climatic processes affect and disrupt technologies through impacts such as extreme heat events and floods (McPhearson et al., 2021).

Recent research adopting integrated perspectives on systems has

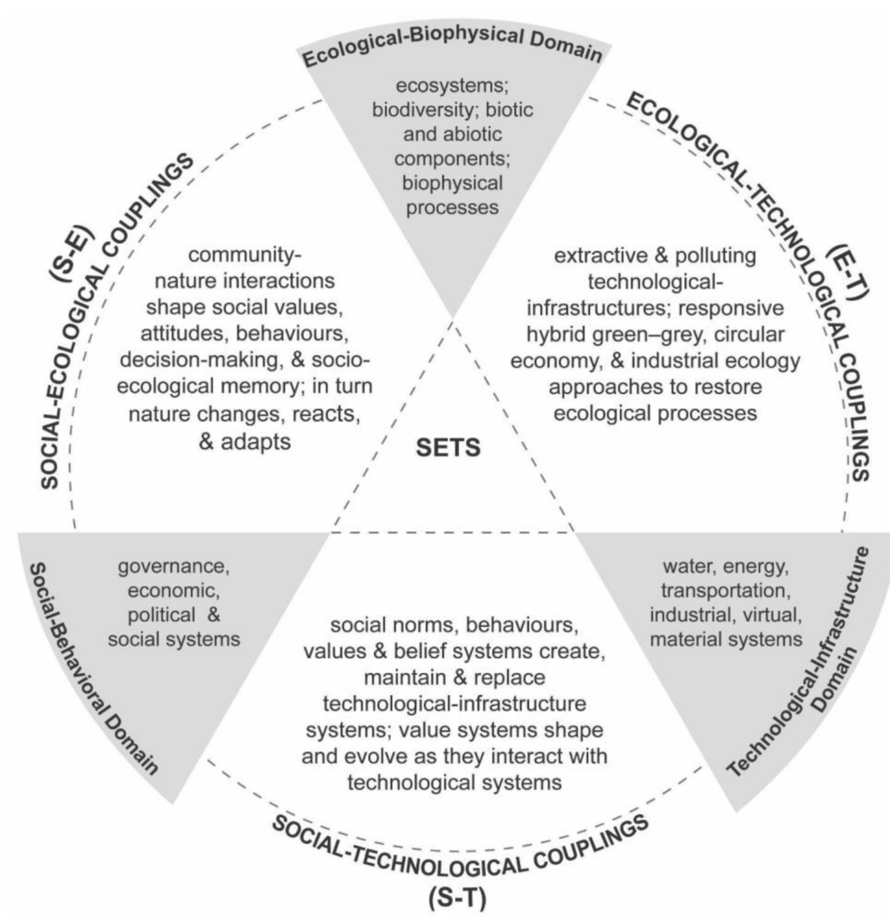

Fig. 1. Social-ecological-technological systems (SETS) framework describing social-ecological (S-E) couplings, social-technological (S-T) couplings, and ecological-technological (E-T) couplings that together interact to define SETS. Adapted from Depietri & McPhearson, (2017); Markolf et al. (2018); McPhearson et al. (2021).

pointed to ways of understanding and examining injustices. For example, Iwaniec et al. (2020) put forth the use of strategic scenarios as mechanisms to deconstruct future visions and include marginalised voices. A better understanding of how injustices are manifested in processes and events can benefit the analysis and development of scenarios, especially in ensuring just climate adaptation measures' formulation within the scenarios. Markolf et al. (2018) recognise that equity and affordability – as implicit justice considerations – are parts of the social dimension of SETS framework. In the application of the SETS however, the analysis does not extend to justice aspects or implications of technological robustness planning. Andersson et al. (2019) point that for planning and designing green and blue infrastructure in cities, different justice dimensions need to be taken into consideration. However, in recent papers applying the SETS framework, considerations of justice and/or equity often remain blind spots (Ahlborg et al., 2019; Markolf et al., 2018).

Similarly, indicators' schemes in addressing injustices or inequalities in SETS have been also developed only to partially represent social-ecological system interactions and often neglecting the technological-infrastructure subsystem. For example, Schröter et al. (2020) developed an analytical framework that amongst others, identifies embedded issues of justice and equity building on a relational ontology of people and nature. However, they only addressed the distributional aspect of justice for social-ecological systems, without accounting for the technological factors and infrastructure that intermediate people and nature relations. Langemeyer and Connolly (2020) position in their framework the social justice dimensions of participation, recognition, and distribution alongside the ecosystem services framework. In this example, the ability of nature to provide not only habitat but also contributions to people has yet to be fully considered. Thus, in our framework, we consider the often-missing capabilities dimension, fundamental for examining and improving ecological justice. These attempts remain limited to sub-system level examinations and lack a more holistic system perspective, or as we argue, a SETS approach in which a justice perspective is integrated and deeply embedded.

2.2. Ecological justice

Ecological justice is a theoretical approach that originates from the well-established environmental justice theory and practice. Environmental justice grounds its tenets in three main dimensions: distribution, recognition, and participation. Environmental justice has long been arguing for the unfair relationship between the distribution of environmental impacts and risks on the vulnerable, marginalised, and minority groups of society (Bullard, 2008; Maantay & Maroko, 2018; Miyake et al., 2010; Temper et al., 2018; Walker, 2009). Linked to the issue of maldistribution is the misrecognition, misrepresentation, devaluation, and a lack of inclusion in decision-making processes that ensure inclusive and transparent democratic participation for all groups of society (Schlosberg, 2012; Schlosberg, 2013; Stephens et al., 2019). Ecological justice captures these dimensions but argues that society cannot be separated from the natural world and just as injustices are committed on people, they are committed to all of nature. Consequently, ecological injustices extend the notions of distribution, recognition, and participation to nature. Additionally, several scholars call for the inclusion of a fourth dimension, capabilities (Fulfer, 2013; Schlosberg, 2012; Schlosberg, 2013; Wienhues, 2017). To build a framework for analysis, we draw from these four dimensions and describe them as follows:

- Distributional justice refers to the equal, fair, and equitable allocation of environmental goods and bads, ecological functions, and benefits (Washington et al., 2018; Wienhues, 2017). On one hand, it highlights the unequal exposure or allocation of toxic, contaminating, or degrading activities on nonhuman life. On the other, it seeks the fair distribution of resources and life-supporting ecological processes to nonhuman life so as they can (co-)exist and flourish.
- Recognition seeks the acknowledgement of social-ecological interconnectedness, nature's intrinsic value, own interests, needs, claims, capacity, and agency to exist, flourish, and adapt to change (Schlosberg, 2013; Strang, 2016; Washington et al., 2018). From a social perspective, it is about acknowledging, appreciating, respecting, and acting upon nature's capabilities, through human-nonhuman relations and mobilisation. Politically, institutions and governments can recognise nonhuman life, exalting their capacities, value, and protection.
- Participation or procedural justice calls for the inclusion of nature in procedural, decision-making processes, where nature is an active agent, and where humans and nonhumans reciprocate and negotiate in a relational exchange (Schlosberg, 2005; Stephens et al., 2019; Strang, 2016). Nature's active voice can be expressed in procedural processes through an understanding of other species' needs, agency,

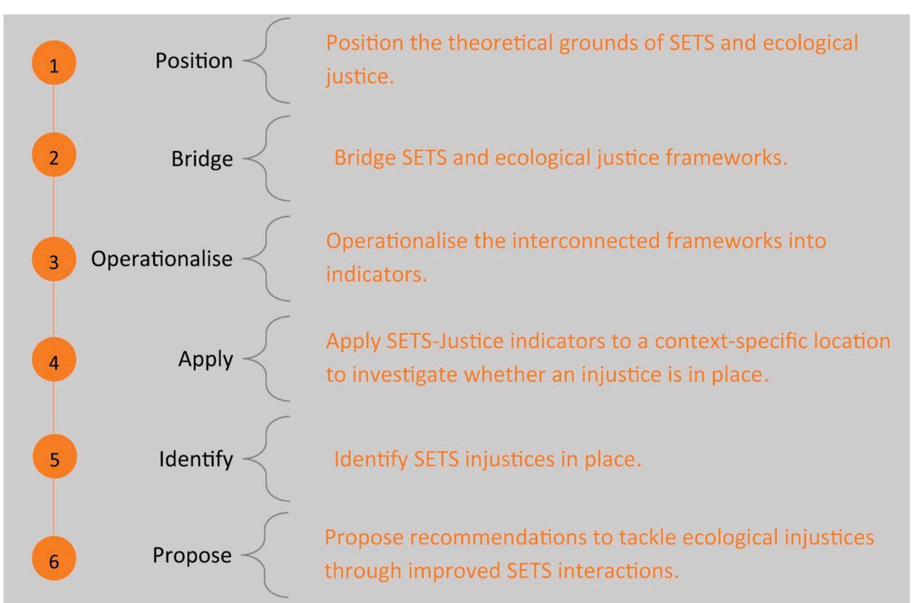

Fig. 2. Six steps taken to integrate and apply a combined SETS and justice perspectives for cities.

and intentionality (Schlosberg, 2005). By representing these voices and positioning them within the community of justice we bring them closer to the political agendas and discussion tables.

- Capabilities refer to nature's integrity, agency, and capacity to sustain life, regenerate and flourish in a state of well-being and in accordance with fundamental ecological processes, functions, and structures (Fulfer, 2013; Wienhues, 2017). Capability underlines all other dimensions, as it is the necessary foundation for life and all its processes to exist. Capabilities also speaks to the capacity of individuals and systems, in this case nonhuman life and ecosystems, to absorb shocks and change - be resilient - in accordance with their needs, vulnerabilities, and capacities. Identifying and mapping these needs and vulnerabilities (Schlosberg, 2012) can lay a roadmap to ensure enough opportunities enable a functioning life (Nussbaum, 2004).

All dimensions are interconnected, meaning that when one dimension is being obstructed, the others are as well (Pineda-Pinto et al., 2021). From an understanding of repositioning human-nonhuman nature relations, we define ecological justice as one that argues for the fair distribution of environmental goods and bads through a recognition of nature's capabilities, capacity to flourish, and be an active participant in shaping its environment (Fulfer, 2013; Strang, 2016; Wienhues, 2017). We thus position our theoretical framework as relational in which injustices enacted upon nature are also enacted on social groups and vice versa; these relationships are fluid and dynamic (Kendal & Raymond, 2019).

We amplify ecological justice further through a SETS framing to bring in the technological-infrastructure dimension, which is fully entangled in notions of environmental justice. For example, the siting of landfills or waste disposal sites in communities where minorities reside (Bullard, 2008), is not only about social drivers or environmental impacts, but about infrastructure as an entangled component of what drives injustice. We explore the influence among SETS in the development of a systems framework to understand and evaluate ecological injustices. We ask the question: How can we comprehensively expose ecological injustices through a SETS analysis? We do this by conceptually exploring the interactions between SETS from an ecological justice lens. As the nature of these interactions is relational, we explore the interactions and dynamics that occur at the intersection of the social-ecological couplings (S-E), social-technological couplings (S-T), and ecological-technological couplings (E-T) (McPhearson et al., 2021).

2.3. Bridging SETS and ecological justice

In bridging and operationalising the ecological justice and SETS frameworks, we identify many commonalities for integration, including their relational nature, capabilities, and agency of each of its components. We bridge these two frameworks to analyse, from a multidisciplinary and integrated approach, the complex dynamics within SETS that produce ecological injustices in cities with the aim to spatially identify intra-urban injustice hotspots. An ecological injustice hotspot is conceptualised as a geographical area in which nature's capabilities are obstructed because they are misrepresented, neither valued nor recognised and have a higher distribution of environmental impacts and risks than other areas within the case study boundaries (Pineda-Pinto et al., 2021). Our main aim is to operationalise a comprehensive framework for analysing complex SETS to be able to identify and understand ecological injustices in place. This process allows high-level concepts and objectives to be broken down to measurable indicators, while retaining the larger systems framing. To examine the synergies between these two frameworks we look at the SETS couplings and their relations to ecological justice's dimensions. This allows us to have a pragmatic approach when identifying variables that can represent these interactions. As these variables are produced in isolation and bounded by their own geographies, disciplinary focus, objectives, epistemologies and methodologies, we need to source them independently and then bring them together to reconstruct a SETS-Justice understanding.

The first step in bridging the two frameworks consisted of an exercise of developing questions that addressed each ecological justice dimension in terms of the SETS interactions (Table 1).

By considering their bridging potential through questions designed to operationalise the related concepts, it allows us to define objectives for each of the coupled SETS-Justice dimensions. For the SETS-Distribution we will identify social-economic activities and/or polluting technological-infrastructure that impact and put at risk social-ecological systems. We do this to understand how these impacts and threats are distributed, and how they obstruct social-ecological functions, processes, and capabilities. The SETS-Recognition coupling's aim is to uncover plans and projects that promote social-ecological stigmatisation, devaluation and marginalisation through uneven technological-infrastructure development. SETS-Participation will identify social capital and civic engagement to protect nature, develop SETS technologies and infrastructure to build social cohesion, networks, and capacity. Whenever possible, it will also explore the degree of diversity of stakeholders within SETS projects and plans. Finally, the SETS-Capabilities coupling will determine the local social-ecological systems, and hybrid green-grey infrastructure' capacity to adapt to disturbances and shocks while providing ecological benefits. Simply, this coupling

Table 1
Ecological justice (EcJ) dimensions and SETS interactions: bridging the frameworks. EcJ dimensions: Distribution (D), Recognition (R), Participation (P), and Capabilities (C).

EcJ Dimensions	*SETS Interactions*		
	Social-technological (S-T)	*Ecological-technological (E-T)*	*Social-ecological (S-E)*
D	*What impacts, risks and threats of infrastructure burden vulnerable social groups? Is basic technological infrastructure (energy, water, food, transportation) equitably accessible?*	*Which technological-infrastructure pollutes and degrades ecosystems? How are these impacts and threats distributed, and how do they obstruct ecological functions and processes?*	*What impacts and risks from socio-economic activities pollute and destroy ecosystems? How are these impacts distributed and which groups are affected?*
R	*Which technological-infrastructure plans are entrenched with devaluation and stigmatisation? Are all values and preferences considered fairly when planning technological-infrastructure?*	*Are ecological principles (to improve nonhuman life and ecologies) incorporated in design and planning of technological-infrastructure components? Are there institutional arrangements for enabling hybrid green-grey infrastructure?*	*How is human and nonhuman nature represented? What is the level of concern for ecosystem health, nonhuman and human wellbeing?*
P	*Which groups are excluded in technological-infrastructure planning and design? What institutional arrangements block transparent and inclusive decision-making?*	*Who is involved in the design and planning of hybrid green-grey infrastructure? Are design and planning processes transdisciplinary? Do they involve multiple stakeholders from different sectors?*	*Who represents nature? Are their processes and platforms to engage with nature, build ecological knowledge, capacity transfer, and better manage ecosystems?*
C	*Is there social capital to develop technological innovations? What is their level of flexibility, adaptability, and robustness?*	*What is the capacity of hybrid green-grey infrastructure to adapt to disturbances and shocks and provide ecological benefits? What is the degree of ecological restoration?*	*What is the state of the local ecosystem's health? Does it allow for non-human life to flourish and exist?*

will identify the SETS resilience for delivering (or not) social-ecological benefits. This conceptual exercise is operationalised in the next section with two sub-steps which include identifying parameters and defining simplified indicators per SETS-Justice dimension.

2.4. Operationalisation of SETS-ecological-justice framework: identifying parameters and indicators

In order to bring this thinking to empirical case studies, we need to operationalise the SETS-Justice dimensions (Step 3, Fig. 2). To answer the questions and objectives developed in the conceptual merging, we define a set of parameters. These parameters provide a mid-level definition of the SETS interactions and the justice dimensions as coupled subsystems that can be measured with established indicators. The final operationalisation step consists of identifying these indicators. As shown in Table 2, several of the proposed parameters overlap and can be represented in different SETS-Justice relations. As such, this can be represented or mapped through many indicators, resulting in repetitive data and many times double or triple counting of similar or exact variables. To avoid this, we present a set of indicators that we consider represent the bridged SETS interactions and ecological justice dimensions. This is a reference list and is presented as an open template which has the flexibility to be adjusted to other needs and capacities. The exercise here is to not to lose perspective on the importance of representing each SETS interaction in the S-T, E-T, and S-E couplings (McPhearson et al., 2021) and its conjunction with ecological justice.

To further illustrate the conceptual operationalisation developed in this section, Fig. 3 presents the merged SETS and ecological justice frameworks and a set of parameters that represent the related concepts. As mentioned earlier, it is important to indicate that this is an experimental exercise, where we lay out the conceptual process for merging and operationalising the SETS and ecological justice frameworks. In this sense, the proposed bridging framework offers flexibility and adaptability to diverse circumstances by allowing the inclusion or modification of the questions, parameters, and indicators as per the needs and capacity of each city. For this paper, after conceptually bridging and operationalizing SETS-Justice, we empirically investigate the methodology with a study case, New York City (NYC). In the case of NYC, the availability of reliable and up-to-date data drove the focus of the methodology towards indicators that emphasised pollution, stewardship, social vulnerability, and ecological health. For other cities, this focus might change depending on the data available and other strategic objectives. The next section focuses on NYC's contextual background and the application of the methodology.

3. Methods

3.1. Case study: New York city

Located in the Northeast region of the United States, NYC is one of the densest and most populated urban areas in the world. It lies within 790 km2 (305 mi^2) and supports a population of more than 8.4 million inhabitants. It is a multicultural space, making this one of the most racial and ethnically diverse cities. The city is composed of 71 Community Districts (CDs), 59 of them inhabited, embedded in five major boroughs – Bronx, Manhattan, Queens, Brooklyn and Staten Island (Fig. 4).

NYC's high degree of urbanization and population density, as well as the concentration of industrial activity in certain areas, have caused important environmental degradation over its history. Examples of environmental degradation vary widely, including the loss of vegetation due to urban development, the discharge of polluted wastewater through the city's combined sewer system (NYC Environmental Protection, n.d.), and one of the largest oil spills in American history in one of the city's most industrialized areas (NYS Department of Environmental Conservation, n.d.-b). Several environmental remediation policies have been implemented in recent years, such as a project to plan a million trees in the city (MillionTreesNYC, n.d.), a green infrastructure plan destined to reduce the volume of combined sewer overflow discharges (New York City Department of Environmental Protection, 2010), a tax abatement for the development of green roofs (NYC Department of Finance, n.d.), and a state-wide program to protect natural heritage (NY Natural Heritage Program, n.d.). Despite its long history of environmental degradation due to the city's growth and activity, NYC is still home to a wide biodiversity, and has over 20% of tree canopy cover, albeit not equitably distributed (McPhearson et al., 2013). Urban forests, wetlands, parks, and waterways compete for space in a highly dense environment, with extreme socio-economic pressures and human-induced impacts. Protection, restoration and rehabilitation of these spaces is critical to safeguard the existence of NYC's rare species, over 1000 native plant species and 26 distinct ecological habitats (McPhearson et al., 2013).

NYC's ecological and technological (*e.g.* infrastructure development and maintenance) challenges are confronted with the city's social disparities that stem from a rooted history of institutional racism in the form of land use and zoning regulations that have created geographies of inequalities (Baptista, 2019). Research focused on NYC has unveiled patterns of inequity in the exposure to environmental benefits, such as access to green spaces, environmental hazards such as exposure to flooding and extreme heat, and anthropogenic hazards such as exposure to pollution (Herreros-Cantis et al., 2020; Klein Rosenthal et al., 2014; Miyake et al., 2010; Sze, 2006). Environmental injustice in the city has progressively gained importance in the city's governance arena. Advocacy groups such as WE ACT for Environmental Justice (WE ACT, n.d.) and the NY Environmental Justice Alliance (NYC Environmental Justice Alliance, n.d.) are examples of local-based organizations whose work focuses on visualizing environmental injustice patterns, empowering communities, and pressing government officials to take action against them. On the legislative side, recent measures have been implemented. Local Law 60, which "requires a study of environmental justice areas and establishes an environmental justice portal" and Local Law 64, which "establishes an Interagency Working Group to develop an Environmental Justice Plan", are examples of measures to incorporate environmental justice considerations into NYC's governance (Baptista, 2019: p. 18). As a result of these laws, the city recently started the development of the Environmental Justice for All report, which will inform the development of an environmental justice plan (NYC, n.d.-b) under the guidance of the Environmental Justice Advisory Board (NYC, n.d.-a), a group composed of advocates, academics and public health experts. As a dynamic city with many pioneering initiatives on both urban sustainability, resilience, and environmental justice, NYC remains a city of challenges and a place to examine complex dynamics for ecological injustices and their relation to social, ecological, and technological infrastructure of the city.

3.2. Geospatial analysis

Based on the methodological operationalisation of the SETS and ecological justice frameworks into measurable variables, the following step is to apply it to our study case, NYC. Regardless of the vast amounts of high quality, up-to-date, and varied datasets that the City of New York generates, sourcing the relevant and matching indicators to our framework is limited by many factors, such as chronological consistency, spatial scale, and public availability of the data. Table 3 describes the indicators generated to map SETS injustices in the City of New York as the most representative variables identified in the previous section. CDs were selected as the spatial units of analysis because local decision-making tends to take place at this scale (NYC Mayor's Community Affairs Unit, n.d.). CDs count with their own boards, which advise elected officials about the needs of their community (NYC Community Board 6, n.d.). City programs such as Cool Neighborhoods NYC (New York City, 2017) and the New York City Community Air Survey (NYC Environmental Health, n.d.) aggregate their reports at the Community District

Table 2
Ecological justice (EcJ) dimensions and SETS interactions: defining parameters and indicators.

SETS Couplings and EcJ Dimensions		*Parameters*	*Indicators*
SETS Distribution	*S-T*	*Distributional interactions between technological-infrastructure and socio-economic activities: Pollution exposure due to industrial or other polluting land uses, (un)equal access and proximity to basic infrastructure and services.*	- *Presence of activities that emit pollutants that may harm people (e.g. number of emitting points, total amounts of pollutant emitted, density of hazardous activities).* - *Distance to basic infrastructure and services (e.g. transport, healthcare, education, food).* - *Water, soil and air quality indicators.* - *Health impacts due to exposure to toxic pollutants (e.g. Visits to hospitals due to respiratory issues due to poor air quality).*
	E-T	*Distributional interactions between ecological integrity and technological-infrastructure activities: Environmental degradation due to urbanization and industrial or extractivist activities.*	- *Hybrid green infrastructure interventions (e.g. number of installations, gallons of water captured)* - *Impacts due to infrastructure and urban development (e.g. impervious land, Water, soil and air quality indicators)* - *- Presence of activities that emit pollutants that may harm the environment (e.g. number of emitting points, total amounts of pollutant emitted, density of hazardous activities).*
	S-E	*Distributional interactions between socio-economic activities and ecological integrity: ecosystem services and benefits distribution, (un)equal access and proximity to green spaces, disproportionate impacts of natural hazards across populations, encroaching urbanization.*	- *-% of areas of habitat restored* - *People and infrastructure exposed to environmental hazards (e.g. extreme heat, flooding).* - *Green spaces accessibility (e.g. distance to parks).* - *- Ecosystem services distributional justice (e.g. differences in flood risk mitigation across communities, unequal heat mitigation by trees across the city).*
SETS Recognition	*S-T*	*Recognition interactions between peoples' norms, behaviours, values, and needs and technological-infrastructure development: adoption of technologies with added social value, plans and strategies to (re)generate community infrastructure and services, acknowledgment of risks and threats of technologies and infrastructure on marginalised or devalued social groups.*	- *Number of plans to deliver infrastructure, technologies, and services to improve social-technical outcomes (e.g. infrastructure plans applying on an area).* - *Types of services and risks related to infrastructure and urban development recognised and prioritized by plans.*
	E-T	*Recognition interactions between ecological integrity and technological-infrastructure activities: Acknowledgment of risks and threats of infrastructure and technologies on ecological integrity; alternative proposals for hybridized infrastructure with biophysical processes and elements to improve ecological resilience and integrity.*	- *Types of environmental impacts and benefits considered in green infrastructure planning (e.g. factors considered or ignored in environmental impact analyses and planning processes, design and siting criteria of green infrastructure).* - *Areas recognized as in need for environmental remediation due to former or current industrial activity or impoverished soil and/or water quality (e.g. percentage of an area marked for restoration, number of sites).*
	S-E	*Recognition interactions between peoples' norms, behaviours, values, and needs, and ecological integrity: Plans to protect species, devalued ecosystems, improve ecological knowledge and attitudes towards ecological systems, impacts, risks and threats of future socio-economic activities on ecosystem services and functions.*	- *Criteria used to determine the ecological value and need for protecting certain areas (e.g. intrinsic value* versus *benefits of humans from nature, species or ecosystem services prioritized, attitudes towards pioneering, alien, or invasive species).* - *Number of environmental protection or stewardship programs applied within a certain area.*
SETS Participation	*S-T*	*Participatory interactions between social groups and technological-infrastructure development: Community- (or diversely) managed decentralised systems (water, energy, food) (vs. centralised, top-down), development of technologies and infrastructure reflect needs and aspirations of minorities or marginalised groups.*	- *Number of community groups advocating for clean technologies and/or decentralised systems (e.g. number of advocacy groups within an area).* - *Social-technical influence and impact of these groups' work (e.g. number, types and outcomes of specific stewardship activities).*
	E-T	*Participatory interactions between ecological systems and technological-infrastructure development: transdisciplinary design and delivery of technologies and infrastructure integrate biophysical processes and elements in decision-making processes; circular economy concepts and industrial ecology approaches are embedded in technological-infrastructure development.*	- *Number of hybrid green-grey infrastructure projects.* - *Life cycle assessments in technological-infrastructure projects.*
	S-E	*Participatory interactions between social groups and ecological systems: Civic engagement for environmental protection, citizen science projects, representation of nature in decision-making processes.*	- *Number of community groups advocating for environmental conservation and remediation (e.g. number of advocacy groups within an area).* - *socio-ecological influence and impact of these groups' work (e.g. number, types and outcomes of specific stewardship activities).*
SETS Capabilities	*S-T*	*Capabilities interactions between social groups and technological-infrastructure systems: Social vulnerability, technological and infrastructure systems vulnerability, mechanisms for risk and hazard detection and prevention.*	- *Social vulnerability (e.g. income, race, education).* - *Infrastructure's degree of vulnerability to different natural hazards (e.g. age, structural integrity, exposure to extreme weather events).* - *Potential cascading effects due to infrastructure failures.* - *- Number, type and quality of mechanisms for risk and hazard detection and prevention (e.g. flood protection mechanisms, early warning systems).*
	E-T	*Capabilities interactions between technological-infrastructure systems and ecological capacities (health and integrity): technological and infrastructure systems vulnerability, ecosystems and species vulnerability, mechanisms for risk and hazard detection and prevention, resilience of green-grey vs. grey infrastructure.*	- *Ecosystem and species vulnerability to being harmed by urban or infrastructure development (e.g. habitat fragmentation, presence of threatened or sensitive species).* - *Infrastructure's degree of vulnerability to different natural hazards (e.g. age, structural integrity, exposure to extreme weather events).* - *-Number, type and quality of mechanisms for risk and hazard detection and prevention.*
	S-E	*Capabilities interactions between social groups and ecological capacities (health and integrity): Social vulnerability (negative), ecosystems and species vulnerability, habitat restoration to improve ecosystem functions, biodiversity and overall human and nature's health and quality; human and nonhuman species needs and their interrelationships, mechanisms for risk and hazard detection and prevention.*	- *Social vulnerability indicators (e.g. income, race, education);* - *Biodiversity (e.g. diversity of ecosystems, species or genes).* - *Landscape connectivity (e.g. mean patch size, edge effects).* - *- Current preservation status (e.g. water, soil and air quality indicators).*

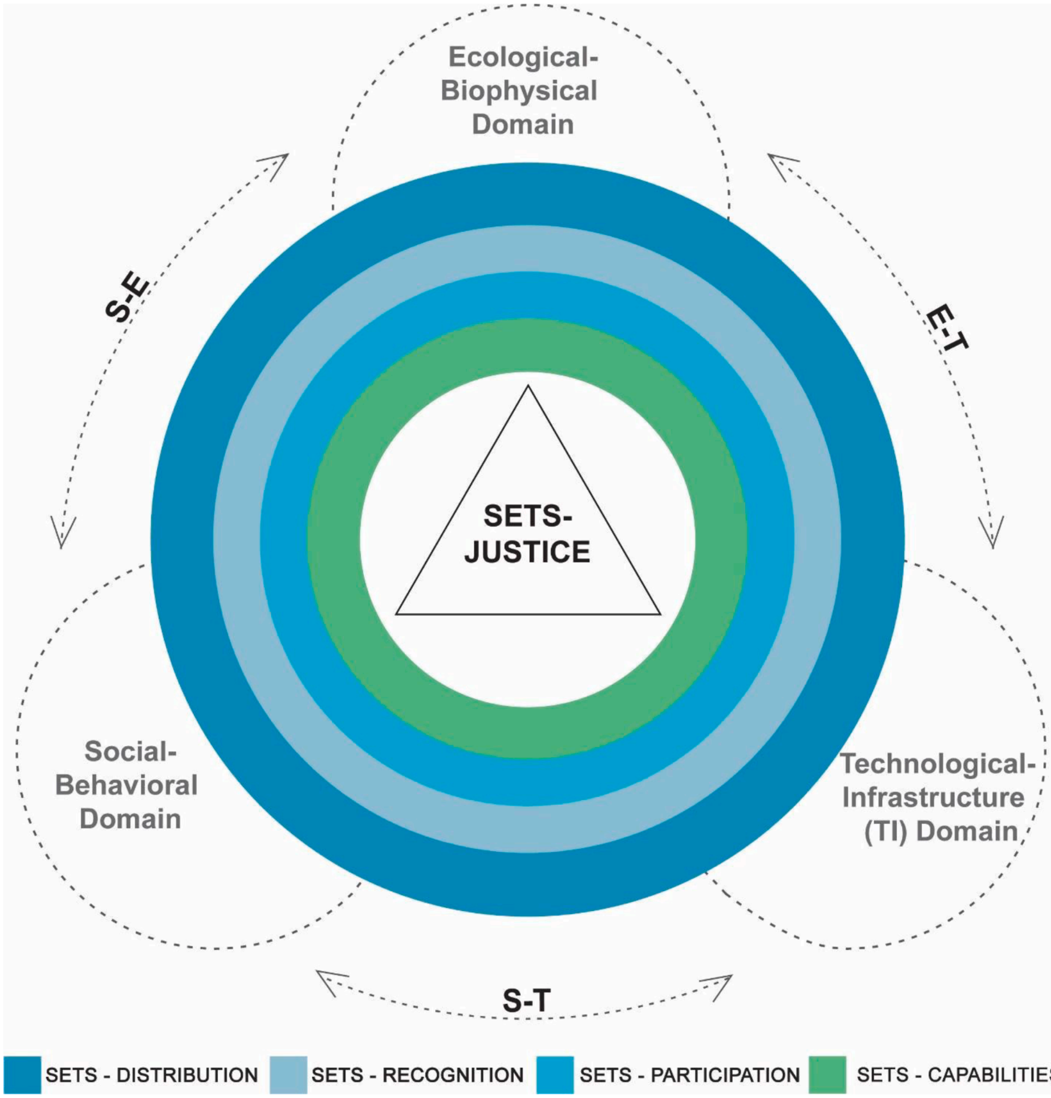

Fig. 3. Integrated ecological justice and SETS frameworks (SETS-Justice): Representation of the SETS interactions bridged with the ecological justice (EcJ) dimensions and their interconnections, which we refer to as SETS-Justice dimensions (*e.g.* SETS-Capabilities). The concentric placing of the circles does not represent a hierarchical relationship.

level. In addition, their relatively limited number (59 districts inhabited, 71 in total) and extensive area allows for simple but straightforward city-wide comparisons. These characteristics make CDs a suitable geographical unit for a first attempt at mapping ecological injustice across NYC.

The indicators for the SETS-Distribution dimension represent the distribution of activities that are considered harmful for the environment. Two datasets were combined to represent these activities, being the Toxic Release Inventory (TRI) and the Combined Sewer Overflow (CSO) outlets that represent discharge points of combined sewer stormwater. The two datasets were combined and a density indicator of the number of sites per km^2 was calculated (D1). The higher the density of pollution sources, the higher the ecological injustice due to the presence of harmful activities. The TRI (US EPA, 2013) tracks activities and industries that discharge chemicals that may pose a threat to the environment and human health. This dataset was filtered so that points reflecting the location of closed industrial facilities were removed. The CSO data was extracted by filtering the inventory of outfalls in NYC (NYC Open Data, n.d.) by type, selecting those labelled as “cso”. By combining stormwater with domestic and industrial wastewater, CSO outfalls are discharge points that may discharge untreated wastewater under moderate or intense precipitation events that exceed the system’s capacity.

The SETS Recognition dimension aims to track areas that have been identified as ecologically relevant by a regulatory framework either because of their need to be restored or handled carefully to avoid environmental impacts, or because of their need to be protected due to their current environmental value. Indicator R1 focuses on areas recognized as in need of being restored. The indicator’s intent is not to measure ecological degradation, but the recognition of the need to restore ecological integrity. Indicator R2 focuses on ecologically valued areas. In both indicators, injustice arises when the acknowledgement for the need to nurture or protect nature is lower. That is, when the number of recognized assets (as in need of being restored or protected) is lower. For R1, we merged the datasets containing E-designated tax lots (NYC Planning, 2018) and New York State’s Remediation Sites (NYS Department of Environmental Conservation, n.d.-a). Tax lots with an E-designation are required by NYC’s planning office to investigate and address specific environmental requirements in order to obtain a building permit or change their zoning (NYC Office of Environmental Remediation, n.d.). E-designations are usually given to tax lots with a land use history that may have led to an accumulation of pollutants in the site, such as a gas station. The dataset with New York State’s Remediation Sites provides the boundaries of sites that are currently undergoing an

Fig. 4. New York City's Boroughs and Community Districts.

environmental remediation process under the management of the State's Department of Environmental Conservation (NYS Department of Environmental Conservation, n.d.-a), including sites under the programs Superfund, Environmental Restoration, Brownfield Cleanup and Voluntary Cleanup. To generate R1, we calculated the number of E-designated and remediation sites per km^2 within each CD. In some cases, a site might have both an e-designation and a remediation site at the State level. To avoid double-counting, we intersected both datasets so that E-designated parcels falling within the boundaries of a remediation site were excluded. For R2, the New York Protected Areas Database (New York Natural Heritage Program, n.d.) was combined with the data showing NYC's Open Spaces & Parks (DoITT, n.d.). NYPAD is a state-level database showing a broad set of protected areas such as conservation and recreational areas, open spaces, and parks. The NYC Open Spaces & Parks dataset was included in order to consider smaller parks that, while their level of protection might be lower, still represent a degree of recognition of the environmental value of open spaces. With both datasets, R2 was calculated as a percentage of each CD's area that is protected.

The SETS Participation dimension is represented by the presence and magnitude of stewardship activity per community district. Indicator P1 represents the distribution of environmental stewardship groups in NYC according to the 2017 STEW-MAP (USDA Forest Service, 2017), which records the areas of activity of civil society groups that protect the environment through conservation, education, champion, and managing activities. Indicator P2 presents the total amount of time invested in stewardship activities on street trees across NYC. This indicator was developed by combining the records of stewardship activity (NYC Department of Parks and Recreation, 2017b) with the city's tree points dataset (NYC Department of Parks and Recreation, 2017a). The first dataset contains a registry of maintenance and improvement activities carried out by stewardship groups on street trees. Each entry (row in the dataset) includes the unique identifier of the tree subject to the activity, the type of activity, and the time invested in it. The second dataset consists of a point shapefile indicating the location of street trees in NYC. By joining both datasets using tree identification fields, the stewardship activity data was mapped and spatially aggregated at the CD level. These indicators identify injustice where the number of stewardship groups and time invested in stewardship activities is lower, indicating a lower participation.

Table 3
List of indicators, definitions, and data sources used for each ecological justice dimension.

Dimension	Name	Description	units	Data Sources
SETS-Distribution	D1	Distribution of activities that harm the environment (+)	Number of points releasing pollutants per km2	Toxic Release Inventory (US EPA, 2013) + CSO outfall points (NYC Open Data, n.d.)
SETS-Recognition	R1	Areas that have been identified as polluted and are required to be restored by a policy (−)	Number of remediation sites per km2	NYS DEC Remediation sites (NYS Department of Environmental Conservation, n.d.) + E-designation sites (NYC Planning, 2018)
	R2	Areas that have been identified as needed to protect or preserve by a policy (−)	% Area that is not protected	New York Protected Areas Database (New York Natural Heritage Program, n.d.) + NYC's Open Spaces & Parks dataset (DoITT, n.d.)
SETS-Participation	P1	Presence of stewardship groups that may advocate for environmental stewardship (−)	Number of stewardship groups	STEW-MAP 2017 (USDA Forest Service, 2017)
	P2	Magnitude of actual effort carried out in environmental stewardship (−)	Time reported on stewardship activities on trees	Stewardship activities (NYC Department of Parks and Recreation, 2017b) carried out in NYC's street trees (NYC Department of Parks and Recreation, 2017a)
SETS-Capabilities	C1	Capacity of the population to adapt to change and shocks (+)	Mean SOVI	CDC's Social Vulnerability Index at the census tract level (CDC ASTDR, 2016)
	C2	Ecological integrity/ecosystem health/Capacity of nature to flourish and adapt to changes in the system (−)	% of total area that is green	NYC's 2017 Land Cover Raster Data (DoITT, 2018)
	C3		Mean Patch Size	

In the Description column, the + or − symbol in parenthesis defines the relationship between injustice and the indicator (*e.g.* the higher D1, the higher the injustice (+), while the higher R1, the lower the injustice (−), meaning that for those indicators with positive values for injustices such as R1, the values need to be inverted).

To measure SETS capacity to flourish and adapt to changes in the SETS (SETS Capabilities dimension), three indicators were used: social vulnerability, green area and mean patch size of green spaces. The first indicator, Social Vulnerability Index, provides a comprehensive index based on 15 socio-economic variables (*e.g.* race, poverty, housing) to assess an area's vulnerability to disasters and shocks (CDC ASTDR, 2016). This index, from a resilience perspective, provides a 'measure' of the SETS capacity, particularly the social-technological components and interactions, to adapt from shocks and impacts. For instance, communities with deeper socio-economic disadvantages, will have less capabilities to prepare, adapt, and bounce back from hazardous events (CDC ASTDR, n.d.). The two remaining variables (C2 and C3) relate to ecological capabilities and provide an integrated overview of NYC's ecological health as a proxy for their capacity to adapt to disturbances and shocks, as well as provide ecological benefits. C2 indicates the percentage of the CD covered by natural land cover (*e.g.* trees, grass, or bare soil), hence accounting for impervious surfaces as an inverse of the indicator. C3 (mean patch size [MPS]) adds further information by evaluating the mean size of individual green patches within the CD. MPS is calculated by dividing the total green area by the number of green patches within each CD. In this study, we assume that a higher mean patch size indicates a higher productivity and resilience within the patch (higher capability), since a smaller patch size may indicate habitat fragmentation and a subsequent increase in the influence of edge effects (Mullu, 2016). By edge effect, we refer to the interactions between two ecosystems (in this case, green spaces and the urbanized environment) that are separated by an abrupt transition (Murcia, 1995), and that may lead to a lower biodiversity than in the ecosystem's core due to such interactions (*e.g.* due to the closer exposure to pollutants, nuisance, and higher winds and sunlight). Both C2 and C3 were developed using NYC's 2017 Land Cover Raster Data (DoITT, 2018), an 8-class land cover dataset with 6 in. of resolution.

For each indicator, CDs were grouped in quintiles and identified as ecological injustice hotspots if they fall within the top quintile or 20%. A score of 1 was assigned per indicator under which a given CD was classified as an injustice hotspot. A total score was calculated by aggregating all the 1 s each CD had obtained. In order to maintain balance across the different EcJ dimensions, which have an unequal number of indicators, the aggregate of the scores was calculated applying weights so that the maximum aggregate of each dimension was equal to 1 (Eq. (1)).

$$EcJ.s = \left(\frac{NH_D}{N_D}\right) + \left(\frac{NH_R}{N_R}\right) + \left(\frac{NH_P}{N_P}\right) + \left(\frac{NH_C}{N_C}\right) \quad (1)$$

Eq. (1): Where EcJ.s is the total score of a given CD, NH_X is the number of indicators within a given dimension that flagged the CD as an injustice hotspot, and N_X is the total number of indicators considered under each dimension.

4. Results

The results from the applied mapping methodology in NYC are presented in two sections. The first part describes the results from each spatially analysed indicator, including also an overview of how each dimension with multiple indicators related to each other. The second part presents the composite map with all indicators aggregated and, just as the indicator-dimensions maps, ranked with the quintile classification method (scale 1–5). The second composite map highlights the ecological injustice hotpots present in NYC's social-ecological-technological interactions.

4.1. SETS ecological injustices per dimension

4.1.1. SETS distribution

Results highlighting the distribution of polluting activities (D1) (density per km^2) reveal that most hotspots occur along the coastline of Manhattan, Brooklyn and Queens along the East River and Newton Creek, a heavily industrialized area. The South Bronx is also highlighted as a hotspot. Part of the CDs classified as a hotspot include five of the seven Significant Maritime Industrial Areas (SMIAs) identified by NYC Planning (NYC Planning, n.d.-a), named Newtown Creek, South Bronx, Brooklyn Navy Yard, Red Hook and Sunset Park. The sixth SMIA, Kill Van Kull, is located in the North of Staten Island at CD 501, which has an injustice score of 4 (4th quintile), and the seventh SMIA, Staten island West Shore, is located in CD 503 - which holds an injustice score of 1 probably due to the large area of the CD compared to the SMIA's area. Low levels of injustice are present in the east of Queens, as well as in its central CDs which present predominantly residential and commercial land uses. Staten Island, in its central and south CDs, show low incidences of injustices – in sharp contrast with its North CD. In Brooklyn, only a few CDs in the center and South of the borough such as Coney Island (CD 313) and Borough Park (CD 312) show lower values for D1.

4.1.2. SETS recognition

The R1 map (Fig. 5) shows that CDs like central and north Staten island, Central Park in Manhattan and other green CDs and parks throughout the Bronx, Queens, and Brooklyn are injustice hotspots. This is because these areas, more ecologically preserved, have no legacy of industrial or polluting activities that may lead to the recognition of a remediation site. The distribution of remediation and e-designated sites highly overlaps with industrial land uses, leading the distribution of R1 hotspots to appear as an inverse of D1 hotspots. CDs that have lower R1 values are located predominantly in Manhattan and Bronx, as well as North Brooklyn. As referenced before, these are areas where industrial land uses dominate. Regarding R2, the percentage of the CD that is not protected as a natural area or a park (R2, Fig. 5) shows high values due to build density in Manhattan's Midtown area. The rest of hotspots are scattered throughout Brooklyn and Central Queens. Lowest values can be observed in the city's big parks (such as Central Park in Manhattan, Prospect Park in Brooklyn, and Flushing Meadows in Queens), in Staten Island's Central Community District, Jamaica Bay in South Queens, and other CDs scattered throughout Manhattan and the Bronx. Most of this responds to a lack of green spaces. When comparing the distribution of values for R1 and R2, we can observe low correlation. Several CDs have similar values for both variables, such as Glendale (CD 405) and JFK Airport (CD 483) in Queens and Gerritsen Beach (CD 315) in Brooklyn.

4.1.3. SETS participation

The SETS Participation dimension analysis highlights the number of stewardship groups that work in each Community District (P1) and the total time invested by stewardship groups in managing street trees (P2). The results show main clusters of injustice located in Central Bronx (CDs 205, 206, 211 and 227) and East Queens according to P1 (CDs 404, 408, 411, 412, 481, 482 and 483). High injustice values are also visible in midtown Manhattan (CD 105) and South Brooklyn (CD 311). Regarding P2, many large parks such as Prospect Park in Brooklyn (CD 355) and Flushing in Queens (CD 481) are injustice hotspots. A possible explanation for this is the dataset's bias (focus on street trees, and not on bigger parks). Half of the P2 hotspots are also P1 hotspots, and the other half is mainly composed of CDs in southern Brooklyn and Queens such as Coney Island (CD 313), Rockaways (CD 414), and Jamaica Bay (484), as well as Southern Staten Island (CDs 503 and 595).

4.1.4. SETS capabilities

The spatial representation of social-ecological-technological capabilities presents three diverse, but complementary variables. Firstly, to understand the capacity of the social domain including its technological and ecological couplings to adapt to shocks and changes, we used the social vulnerability index (C1, Fig. 5). The highest values for this variable are centered in the Bronx and Northern Manhattan. Two Eastern CDs in Brooklyn are also hotspots. Medium to high degree (3rd and 4th quintiles) of social vulnerabilities are present throughout Brooklyn. Queens, Staten Island, and Central and South Manhattan have values ranging from low to medium (1st to 3rd quintiles). Regarding C2 (percentage of green space) and C3 (mean patch size), which indicate capabilities in the form of ecological integrity, results are very similar. Lowest capability takes place in areas with high built density such as CDs in central Manhattan, East Williamsburg (CD 301) and Bath Beach (CD 311) in Brooklyn, and Corona (CD 404) in Queens.

4.2. New York city SETS-justice hotspots

Different from the previous section, in which we untangle the similarities, differences, and relationships between each indicator and their dimensions, in this section we explore the integration of this data through the spatial aggregation of all indicators. Fig. 6 offers a composite visualisation of the SETS-EcJ couplings.

CD 480 - LaGuardia Airport obtained the highest injustice score by being flagged as a hotspot according to five indicators. This result comes as no surprise, given that this area has a heavy industrial use, with ecosystems being degraded and not restored, as well as no active communities mobilising around social-ecological issues. The other airport in the city, JFK (CD 483), is also among the CDs that obtained a high injustice score (Table 4), along with areas in lower Manhattan (such as CDs 106, 102, or 104), where densely urbanized area with mixed land uses combine a lack of green spaces (indicators C2 and C3) and a high presence of industrial areas (captured in indicator D1). The main parks in Bronx, Van Cortlandt and Pelham Bay Park (CDs 226 and 228) also appear high in the table, regardless of their high degree of naturalization. Among the CDs with the highest injustice scores, only those CDs in the Bronx were identified as hotspots according to C1 (social vulnerability). This comes in agreement with earlier studies that indicate a connection between social vulnerability and ecological justice considerations (Florida, 2017).

Indicators R1 (lack of areas in need of restoration), P1 and P2 (magnitude of environmental stewardship efforts) tend to overlap across the CDs with the highest scores. In the airport areas, this shows the impact of social capital and civil society capacities in restoring nature's agency. The lack of stewardship efforts acts as amplifier of ecological injustices in place; simply it is where nature is losing or has lost its agency. The interesting case of parks as ecological injustice hotspots is addressed below in the discussion section.

Strong correlations are identified across the indicators (Supplementary Information S2, Figs. 1 and 2). For example, indicators C2 and R2 show a correlation coefficient of −0.85, implying that the percentage of green spaces is highly correlated with the percentage of the CD being protected. A moderate correlation (0.4) between C1 and C2 indicates that CDs with a lower percent of green spaces tend to show higher social vulnerability, in line with previous environmental justice studies carried out in NYC (Herreros-Cantis & McPhearson, 2021; Miyake et al., 2010).

Fifteen CDs have a score 0 for all eight indicators. These CDs are present throughout the five boroughs. Comparably, five occur in Brooklyn, while three of them are in Manhattan, Queens, and Bronx. Staten Island only has one CD scoring the lowest degree of injustice. These CDs do not have a heavy presence of manufacturing or industrial zones, particularly in comparison to CDs with high degrees of injustice. These low injustice CDs tend to have a balanced mix of green space and residential land uses (NYC Planning, n.d.b). This indicates that urban forms with presence of green space ameliorate and even balance other drivers of injustice in place.

5. Discussion

The results that emerged from applying the methodology in NYC revealed which CDs have the highest and lowest scores in terms of ecological injustice. It also exposed the variability within each indicator and dimension of justice, pointing towards the importance of analysing

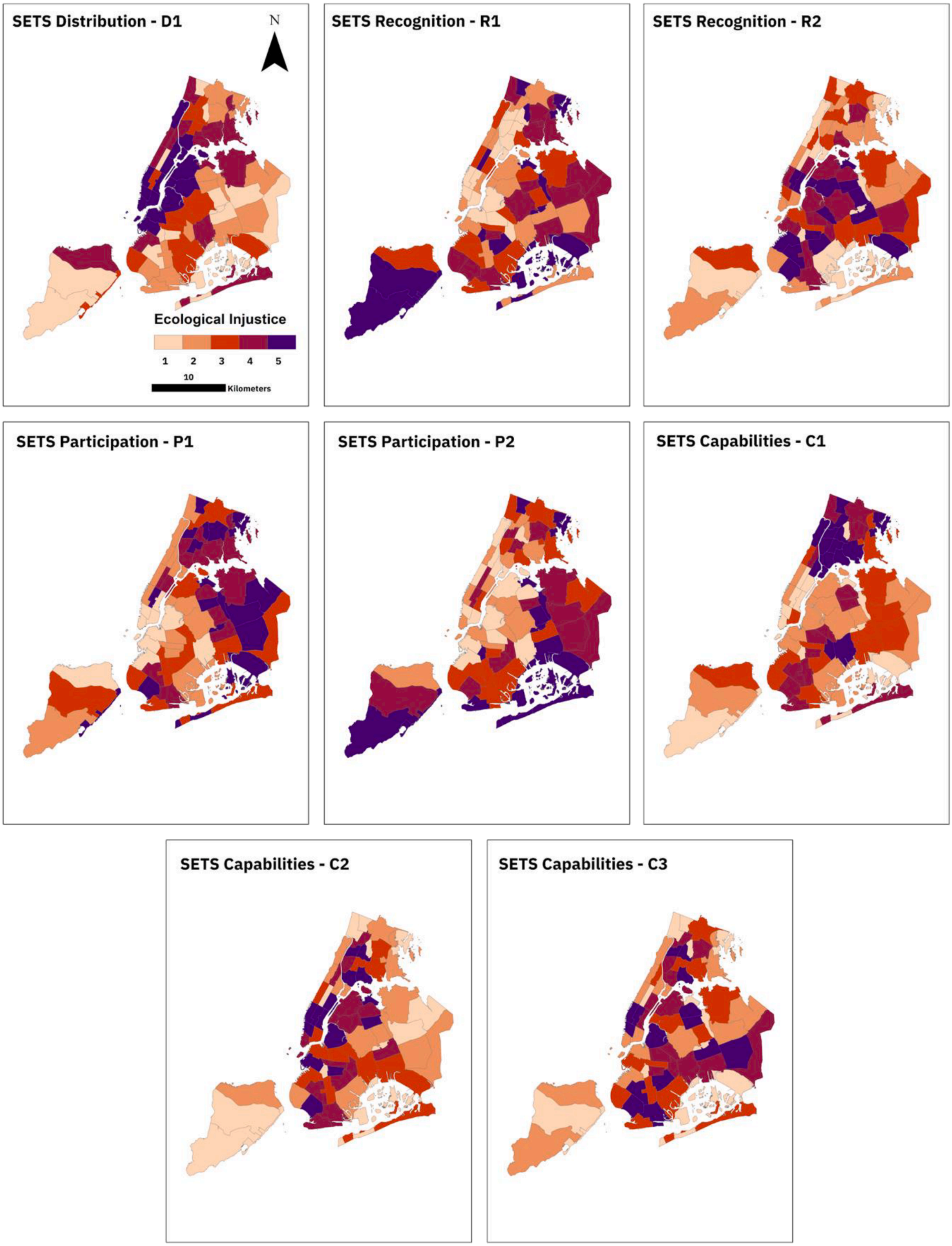

Fig. 5. SETS Ecological justice indicators across New York City's Community Districts. Ecological Injustice corresponds to the quintile classification of each indicator. Quintile 5 (darkest colour) indicates the highest quintile and highest injustice. In those cases, in which the relationship between the indicator and injustice is negative (see Table 3), the scale has been inverted so that the lowest quintile receives an injustice score of 5. CDs with an ecological injustice score of 5 for a given indicator are considered SETS injustice hotspots.

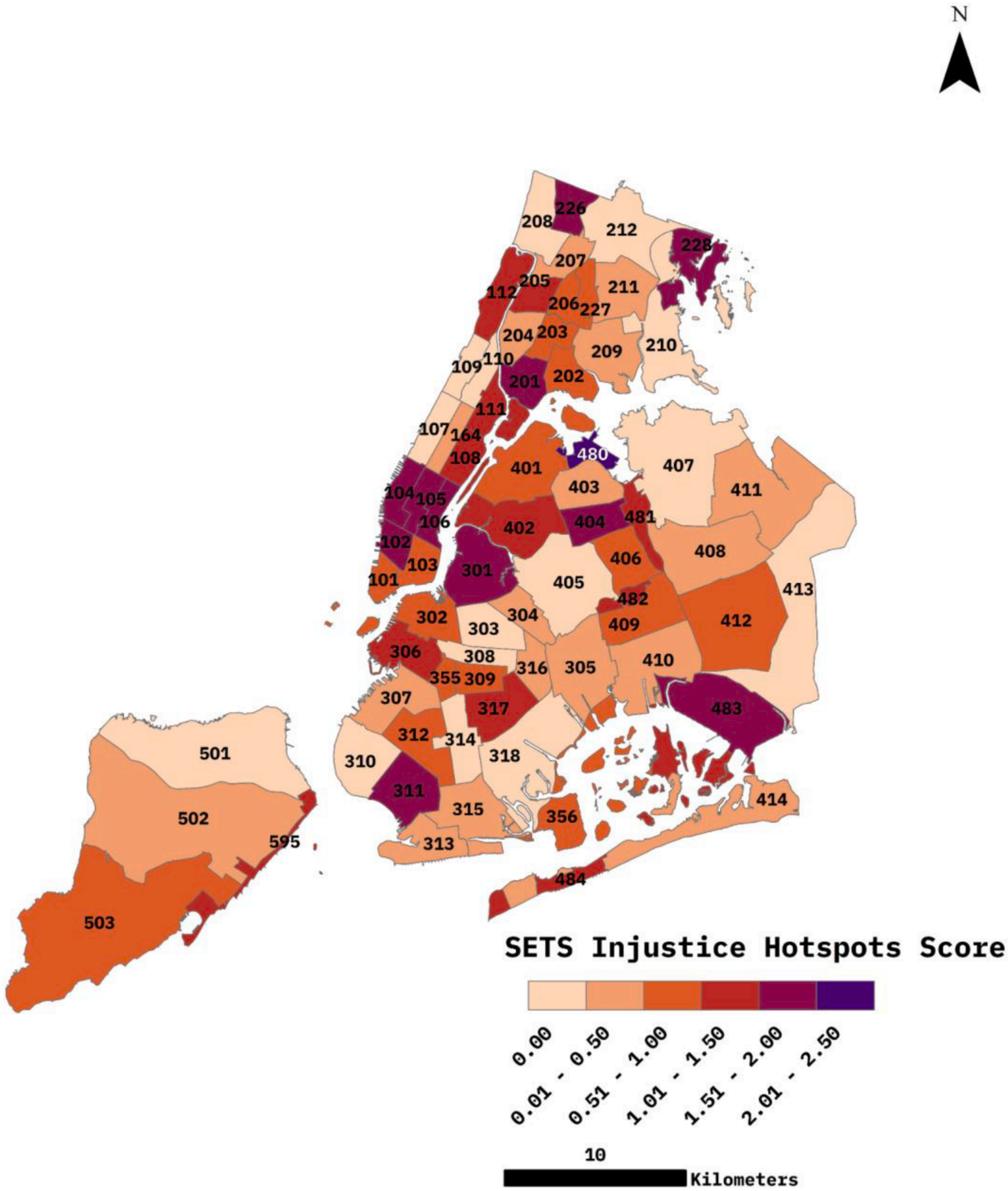

Fig. 6. SETS Injustice Hotspots Score per Community District (CD). Each CD shows the weighted sum of the number of indicators according to which it was in the top quintile (Eq. (1)). The weights were applied in the sum so that each dimension sums one single point to the score, making the maximum possible value 4. The map's legend uses quantiles to set its break values.

Table 4
SETS-EcJ Hotspots: Community Districts with highest aggregated injustice score. A complete version of this table with the rest of the CDs can be found in the Supplementary Information (SI) S1.

Borough	CD	Score	Indicator							
			D1	R1	R2	P1	P2	C1	C2	C3
Queens	480	2.33		*	*	*	*		*	
Queens	483	2		*	*	*	*			
Bronx	226	1.83		*		*	*	*		
Bronx	228	1.83		*		*	*	*		
Manhattan	106	1.83	*		*				*	
Brooklyn	311	1.67			*	*			*	*
Queens	404	1.67			*	*			*	*
Manhattan	105	1.67			*	*			*	*
Bronx	201	1.67	*					*	*	
Manhattan	102	1.67	*						*	*
Manhattan	104	1.67	*						*	*
Brooklyn	301	1.67	*						*	*

SETS-Justice through different lenses to be able to provide more strategic, context-specific solutions. Our research also revealed that injustices in place vary and are shaped by different drivers and conditions. As such, they need adaptive planning that is based on evidence from integrated perspectives such as the SETS-justice framework we propose here, to inform an integrative agenda to tackle such urban challenges in a systemic and place-focused way.

5.1. Variability within SETS-justice dimensions

The spatial analysis presents a visualization of where the injustice hotspots are occurring per indicator and dimension (Fig. 5), and reveals not only similarities between dimensions, but also a shifting of hotspots throughout NYC, depending on which SETS-Justice dimension it is viewed from. Overall, there are deeply rooted or systemic injustices across the city and our analysis reveals where 'thickening' of this injustice and potential eroding of urban resilience is spatially located. The shifting of the injustice hotspots implies that injustice is dynamic and also dependent on how it is examined. This further relates to the fact that different areas can be identified of interest for understanding SETS-Justice dynamics as well as for examining which regeneration programs and social policy initiatives are effective or not. For instance, injustices that occur due to a lack of recognition and participation shows wide variation across all indicators. However, several CDs show mirroring similarities between R1 (areas that have been identified as required to be restored by a policy) and P2 (magnitude of actual effort carried out in environmental stewardship). For these particular areas, the results indicate a need to increase institutional spaces and mechanisms for participation, empowerment, activation of communities, and connection to place from multiple actors to increase stewardship and community engagement and empathy; which in turn would improve the deficiency identified in R1. Finding overlapping deficiencies (injustices) throughout the different SETS-Justice dimensions offers opportunities to develop synergistic, multifunctional strategies to address them.

There are 12 CDs that are hotspots due to lack of participation, both in terms of the number of stewardship groups (P1) and restoration efforts (P2). Two of these CDs are airports, and the rest of them are parks mainly located in Queens. These parks are managed by NYC's Department of Parks and Recreation, which even though have shown advancement in developing policies and programs to improve civil society involvement and engagement, still face barriers (Baker, 2014). Our study reflects this situation and highlights differences between places that require different approaches to improve civic stewardship, which may include re-thinking top-down planning processes versus more engaging modes of participatory planning, reconsidering community partnerships, designing activities and events that respond to local needs and offer diverse stewardship opportunities (Baker, 2014).

When comparing the three indicators for SETS-Capabilities, there are three CDs that are hotspots (top 20% quintile score) for the three variables in the Bronx. Queens and Brooklyn, on the other hand, have the highest number of CDs with the lowest values, (1st quintile), an expression of higher capabilities from a SETS perspective to adapt to changes, shocks, and injustices. From a comparability lens, D1 and C1 have similarities from an environmental justice perspective, but when comparing D1 to C2-3, there are striking differences. Diminished social-technological capabilities tend to be related to higher distributional injustices and this is evident particularly in the Bronx. However, when looking at ecological capabilities, higher injustices tend to 'pop up' throughout Queens and Brooklyn - not particularly matching higher social distributional injustices. As a crucial dimension underlying all others, understanding which regions have high or low capabilities can inform both urban planning for regeneration project development (especially through targeted nature-based solutions) and social policy programs to tap into the improvement of capabilities or aim to build capabilities respectively. Overall, variability of injustices that is revealed by our integrated SETS-Justice framework showcases that an integrated perspective does not nuance spatial representation, but rather allows for a dynamic representation of injustice to be revealed.

5.2. Blind spots of ecological justice research in New York city

The methodology of an integrated SETS and ecological justice framework and its application in NYC offers not only an alternative lens to explore issues of justice, but it also highlights similarities and differences between the more traditional research on justice in cities. NYC is well studied in terms of social and environmental justice. While initially, environmental justice studies in NYC and other U.S. cities focused on hazardous land uses and activities that impacted low-income communities and communities of color by exposing them to toxic pollutants (Bullard, 2008; Sze, 2006), in recent years, environmental justice has evolved its research focus to incorporate vulnerabilities and risks. Some of these include the uneven distribution of natural hazards such as flood risk (Herreros-Cantis et al., 2020; Maantay & Maroko, 2009; Tate et al., 2021) and extreme heat (Klein Rosenthal et al., 2014), the uneven distribution of parks, green spaces and green infrastructure (Herreros-Cantis & McPhearson, 2021; Meerow, 2020; Miyake et al., 2010; Rigolon, 2016), and the potential gentrification effects that urban greening may trigger (Curran & Hamilton, 2012; Maantay & Maroko, 2018).

Compared to some of these studies, our findings corroborate that areas burdened with social and environmental injustice, such as several CDs in the Bronx and Brooklyn (de Sherbinin & Bardy, 2015; Herreros-Cantis et al., 2020; Herreros-Cantis & McPhearson, 2021; Maantay & Maroko, 2018), have an overlap with our study showing higher degrees of ecological injustice. However, our study highlights more differences than similarities with these studies. A particular reason for this is that many studies focus on a particular vulnerability and/or risk that, in turn, tends to emphasise certain urban geographies, such as coastal regions, denser districts, or other spatial areas which are classically known as environmental justice communities. For example, where the aim is to investigate flood risk and social vulnerability (de Sherbinin & Bardy, 2015), which can be aggregated with factors of industrial pollution and contamination (Bautista et al., 2015), such studies or mapping tools concentrate in the coastal areas of NYC.

Rather than focusing on specific vulnerabilities and geographies, our study offers an integrated, multi-focal perspective, with different angles of analysis across the landscape. In comparison to many studies on justice in NYC, the nuance of our study is in showing the heterogeneity of ecological injustice across all boroughs, which do not cluster necessarily in the most socially vulnerable areas; exposing blind spots that classic environmental justice studies may overlook. In addition, the varying degrees (low to high) of injustice across the landscape offer urban planning and design a systematic and site-specific assessment of social-ecological needs and deprivations. Thus, while areas with high degrees of SETS injustice can guide the deployment of targeted, strategic, and immediate nature and people-based actions, areas with lower scores could benefit from other, perhaps long-term, nature-based solutions approaches.

5.3. Planning implications

The finding that all the four hotspots, occurring in Manhattan, Bronx, and LG Airport show a high degree of injustice according to C2 (% of the CD's land cover being natural), also corresponds with the Nature Conservancy Urban Forest Plan's findings. Their study found that although 40.5% the city's land is green cover (landscaped and natural), it also shows an uneven distribution of green spaces amongst the five boroughs - Staten Island has more than 50% of forest coverage, while Manhattan and Bronx only 3 and 19% respectively (Pregitzer et al., 2018). However, NYC has seen in the last decade the introduction of policies to increase forest canopy such as the MillionTreesNYC Initiative (Campbell et al., 2014) and the NYC Cool Neighbourhoods (New York City, 2017). Given the recent implementation of these policies, the spatial and social-ecological effects in the landscape will only be seen in the following decade, with an expected decrease in injustices.

These injustice hotspot areas have been the target of a number of NYC plans, programs and policies. Among the many strategies laid out in OneNYC's 2050 (blueprint for a sustainable, fair and strong future), initiative 10 acknowledges '…the links between the city's natural, recreational, and cultural spaces' and their importance '…for recreation and physical activity, reduce pollution, offer habitat for flora and fauna, and help mitigate the impacts of climate change' to improve health and wellbeing (New York City, 2019: p. 15). This is reflected in the strategy's plans to increase walking accessibility to these spaces for all New Yorker's, specifically through the Community Parks Initiative (CPI), the upgrade of existing parks through Anchor Parks initiative, as well as improving waterfront accessibility. Nonetheless, this strategy has a strong social and technological-infrastructure focus, with little connections and references to the ecology, quality of green spaces in terms of ecosystem services and biodiversity, and in terms of increasing ecological resilience. Despite a recognition of social-ecological connectivity, these strategies and projects reflect a highly anthropocentric focus, with particular attention to air pollution and its intervention from a health equity perspective. Although social and environmental justice is acknowledged throughout the literature, policies, and laws in NYC, the connection between environmental and ecological justice is still lacking.

From a planning perspective, our study provides a systematic approach that not only accounts for risk and vulnerabilities in relation to social characteristics, but also that, from a social-ecological-technological relational lens, incorporates the capabilities and resilience of urban ecosystems. This expands the traditional lenses of justice focused on social deprivations, and includes nature as a bearer of injustices, exploring how social and ecological relations shape, enhance, or exacerbate injustices. In this way, social-ecological heterogeneity of injustices across the landscape in NYC are spatially identified and forces us to question which peoples and natures are bearing these injustices, but also to (re)think how to address them. Rethinking how we address these injustices has to start by establishing a vision that puts nature at the forefront of urban planning and decision-making and promotes urban strategies that minimise harm and deliver benefits to both people and nature. Understanding and recognising people and nature's capabilities through a SETS-Justice lens can better help us navigate the conflicting and complex processes embedded in city planning. Identifying ecological injustice hotspots provides strategic guidance for targeting areas with specific requirements and identified deprivations. Specific actions can include the enabling of pluralistic participatory processes that recognise nature as an active agent, with specific needs and capacities, and tailoring specific measures to address rehabilitation or protection of capabilities through nature-based strategies.

5.4. Limitations and future research steps

The application of the operationalized framework through a spatial analysis is experimental, and with it, certain limitations have been identified and should be addressed in future iterations. To begin with, ecological justice hotspots are bounded and framed by the types, availability and temporal and spatial consistency of the data. Certain processes and functions may be overlooked due to limitations in the data. For example, indicator D1 considers the location of pollutant emitting sites, but does not take dispersal processes into account. In large case study areas, this might lead to downplaying the impact of pollutant discharges downstream of water systems or areas affected by the transport of pollutants by the wind. In addition, the indicator does not account for the amounts or types of pollutants emitted per point. Nevertheless, the use of TRI and CSO data is defensible from a replicability standpoint, since these are state to nation-wide available datasets. More broadly, the distributional dimension of the study, measured through indicator D1, is strongly focused on ecological degradation caused by the discharge of pollutants into the environment. However, other spatially explicit activities that hamper ecological integrity may be considered, such as urban or infrastructure development, or the overexploitation of natural resources through extractive activities like mining or logging. Users of the proposed methodology may incorporate this information if available and relevant to their local context. In addition, future applications of this framework may require adding, keeping or removing variables based on the correlations observed across the indicators analysed in this exploratory study (see SI 2 for a correlation matrix of the indicators analysed). For example, the two indicators representing ecological capability, C2 (percentage of the total area green) and C3 (mean patch size) show a strong correlation (corr. coefficient = 0.75), suggesting a high relationship that might induce double counting.

The analysis carried out highlights in its results two main parks as injustice hotspots. These parks (Van Cortlandt and Pelham Bay Park; CDs 226 and 228), both located in the Bronx, belong to a series of major parks in NYC that are self-contained in a single CD due to their large size. (*e.g.* Central Park in Manhattan, and Prospect Park in Brooklyn). Further examination of the indicators that revealed the need to treat NYC's major parks as special, outlying cases. The application of indicator R1 in natural, protected areas will predictably classify them as injustice hotspots due to a lack of development and industrial activity. Might data availability allow for it, applications of the indicator may limit the measurement to areas that should be remediated rather than the entire CD. Indicator P1 shows major parks as hotspots due to their highly centralized management, as well as a possible bias to represent stewardship groups focused on smaller locations. Indicator P2 (time invested in tree-stewardship activities by local community groups) emphasizes street trees over parks. If the data were available, other trees (*e.g.* park trees) or activities (*e.g.* cleaning parks or riverbanks or planting new vegetation) could be incorporated to the indicator set in order to provide a fuller picture of the environmental stewardship activities in the studied area. Finally, C1 highlights the parks as injustice hotspots due to the high social vulnerability of the surrounding census tracts that overlapped with them during the spatial join operations. Given the exploratory nature of this case study application of a broader EcJ framework, major parks have been treated as equal parts of the sample. However, these results should inform future decisions about the spatial resolution and sampling of spatial units in NYC and other locations.

Finally, CDs were used as the mapping scale aiming to provide a high level, city-wide identification of ecological injustices across the city given their role in local governance and decision-making. In addition, the broad scale of the CDs allowed us to combine a wide variety of data available at different spatial resolutions. However, the methodology suggested should not be seen as a definitive inventory of specific injustices, which may require a finer approach in order to avoid obscuring injustices happening at a finer resolution as exemplified in environmental justice studies such as Maantay and Maroko (2009). As a complement of this analysis that compares CDs, future iterations of this framework should perform intra-CD assessments within each CD to identify injustice hotspots at the local level. The value of such an approach would be to identify ecological injustice hotspots even in those CDs that do not come out as such in a city-wide comparison. Given the role of CDs in the city's governance and planning, a fine resolution application of this framework would enable their representative boards to identify areas on which to prioritize interventions.

It is important to consider that subsequent studies that zoom into a particular CD should consider combining the methods of this study with others such as interviews with key stakeholders (from policy and communities) in order to formulate nature-based actions and strategies that adequately respond to the local context. Therefore, to complement and improve this methodology, we recommend future studies that include participatory methods and analytical tools that grasp with a finer lens social-ecological perspectives and complexities that can tailor people and nature-based solutions and actions that address local needs and deficiencies. Future research directions can include combining this methodology to identify intra-urban injustices, with methodologies that use participatory methods, such a public participation GIS (Raymond et al., 2017), as well as approaches that relate social practices and ecological connectivity, and social-ecological network and flows (Egerer et al., 2020; Ernstson, 2013). This will capture local social-ecological perspectives and complexities that can provide more tailored nature-based solutions and other planning strategies to address ecological injustices in SETS couplings. To add to this, we suggest that future studies need to incorporate policy impact analyses to trace policy effectiveness of measures and programs onto areas that are consistently identified as areas of systemic injustices across research of social, environmental and integrated justices (like ours) and map the transformative impact of those programs over the years.

6. Conclusion

In our paper the SETS and ecological justice frameworks were brought together and applied in NYC with the objective to bring forward a novel analytical approach of ecological justice in cities which extends the notions of justice to nature. We set out to provide an alternative lens to understanding the different dimensions of justice through the SETS couplings. Results revealed variability within each dimension of justice, with areas having high levels of injustice from a lack of recognition, participation, distribution, and capabilities. These findings highlight the importance of disaggregating the dimensions of justice to understand specific needs and deficiencies in different areas and be able to provide more context specific actions that respond to the local conditions. Additionally, this analysis revealed that SETS-Justice hotspots differ when compared to other justice studies of NYC. As the primary focus of these studies consists of social and environmental justice analyses, they lack an ecological justice lens, which shows deficiencies in CDs that are normally not captured in other traditional analyses of justice.

Analysis of SETS-Justice through different lenses, specifically through each of the four dimensions and their indicators, can help uncover if an injustice hotspot is deficient or lacking in social-ecological recognition and participation, if it is being unequally impacted by harmful activities, or if its capabilities are depleted. This in turn can inform strategies and actions that cater for more strategic, context-specific solutions. For example, for a place that is lacking social-ecological participation, policies, and projects can target the creation of institutional spaces and conditions for community engagement, capacity building, and ways to strengthen ecological knowledge.

One of the contributions of the SETS-Justice framework is its ability for adaptability in terms of how the SETS-Justice dimensions are operationalised. The identification of parameters to represent these coupled dimensions is driven by questions that emerge from the conceptual merging. Answers to these questions can vary according to each city's context, capacities, and needs. The flexibility of this framework can allow other cities to apply it and adjust it to their local circumstances, data availability, and potentially expand the 'types' of parameters and indicators with further ecosystems mapping, modelling, and participatory approaches. For example, for many cities it will be critical to integrate indigenous perspectives to this framework, enriching and broadening the scope of voices that are captured. Our methodology presents an opportunity for cities to uncover blind spots and target ecological injustices through different mechanisms, including ways to revalue social-ecological systems, recognise their capabilities, and identify ways in which nature can be included in decision-making processes. This may help lead the way to identifying, designing and planning for different nature-based solutions that tackle ecological injustices in place, enabling more effective and inclusive governance of urban SETS.

CRediT authorship contribution statement

Melissa Pineda-Pinto: Conceptualization, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Pablo Herreros-Cantis:** Data curation, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Timon McPhearson:** Conceptualization, Writing - review & editing. **Niki Frantzeskaki:** Conceptualization, Writing - review & editing. **Jing Wang:** Methodology. **Weiqi Zhou:** Methodology.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2021.104228.

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