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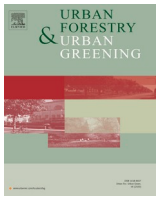

Original article



Land use and socio-economic impacts of co-created nature-based solutions: a case study for Tampere, Finland

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ABSTRACT

Urbanization is currently one of the most urgent planning challenges, weakening cities' resilience to and accentuating impacts of climate change. European cities are already facing the impacts of climate change and unsustainable urbanization, trends only expected to worsen with time. Nature-based solutions (NBS) are climate change mitigation and adaptation measures that are acknowledged to have the potential to steer urban form as well as to influence socio-economic dynamics. However, there is a lack of studies that evaluate such impacts. Hence, the objective of this study is to develop and apply an integrated approach that allows for the co-creation and socio-economic assessment of NBS scenarios. To this end, a NBS co-creation workshop procedure is developed and integrated with a spatially-explicit hedonic pricing simulation model, as to allow for the co-development, -assessment and -discussion of NBS scenarios for the case of Tampere (Finland). Results show that NBS land use and socio-economic impacts are mainly dependent on the attractiveness level, size and accessibility of NBS. In fact, for an already green city such as Tampere, low attractive NBS may just have local positive impacts, even causing a small urban expansion (green roofs scenario) or close to null impacts (street trees scenario). Only the, highly attractive, river daylighting scenario led to an urban contraction and more dense settlements and increased housing prices. Overall, for urban areas with an already large green urban share, more attractive NBS should be implemented for better land use and socio-economic impacts.

1. Introduction

Urbanization is currently one of the most urgent planning challenges, weakening cities' resilience to and accentuating impacts of climate change (Acosta and Haroon, 2021; Lafortezza and Sanesi, 2019). European cities are already facing the effects of climate change with increasing intensity and frequency of extreme events. This pressure is expected to increase in the future, given the growth in urban residential population in Europe from 73% in 2015–82% by 2050 (EC, 2015). This, in turn, will emphasize the demand for alternative and more sustainable planning solutions, representing an opportunity to foster urban sustainability that is dependent on mitigation and adaptation measures to climate change and unplanned urban growth (De Los Rios-White et al., 2020; EC, 2015).

Land use conversion from natural to built areas is increasing, promoting spatial conflicts, soil impermeabilization, vegetation and biodiversity loss, flooding, heatwaves, air and water pollution, and isolation from nature. These impacts reduce the quality of life, mental well-being and physical health, and encourage gentrification and social inequality (Kabisch et al., 2022; Sarwar & Alsaggaf, 2020). Hence, land conversion is considered a critical planning and policy obstacle to sustainable urbanization and one of the main indicators of socio-economic and environmental change. Hence, the European Commission proposed an action plan to hinder land uptake in order to attain "no net land take" by 2050 (Marando et al., 2019). Urban form is a reflection of planning policies and household preferences, which aim to improve housing conditions, reduce commuting distances and increase access to good quality green spaces subject to income, housing and commuting costs as well as land

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availability (Mendonça et al., 2020). Nevertheless, unplanned urban growth usually leads to scattered, fragmented and low-density development patterns (i.e. urban sprawl) that exacerbates the above-mentioned environmental, social and economic impacts (Acosta & Haroon, 2021; Mendonça et al., 2020).

Nature-based solutions (NBS) are increasingly acknowledged as suitable alternatives to traditional solutions to mitigate and adapt to the negative impacts of urbanization, economic growth and climate change. NBS can be defined as "solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience" and are considered "resilient, adaptable, resource efficient, locally adjustable, equitable and optimised solutions to maximize opportunities and improve well-being" (EC, 2021a, p.17). The United Nations Environment Programme (UNEP) also defines NBS as "actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems" and "address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human-well-being, ecosystem services, resilience and biodiversity benefits (UNEP, 2023, p.1).

There are several NBS examples, such as green roofs, street trees and river daylighting (for a complete list, see EC, (2021a)). Green roofs can be defined as rooftops that are vegetated and are a suitable option for dense urban settings that lack space for green infrastructure, especially because impervious surfaces, such as building roofs, account for 20–25% of the total urban area (Joshi and Teller, 2021). Their specific benefits include flooding control, carbon sequestration, biodiversity promotion, food provision, reduce heatwaves and indoor temperature, reduction in energy consumption and noise as well as recreational, well-being and aesthetics benefits (Liu et al., 2021; Pereira and Baró, 2022). Street trees also have the ability to be implemented in dense residential areas and their benefits include carbon sequestration, biodiversity improvement, temperature and flood regulation, building cooling and increase in property values (Anderson & Gough, 2022; Reynolds et al., 2017). Finally, river daylighting includes the opening of previously altered and buried watercourses, creating new blue and green spaces that improve water quality, reduce flooding risk, improve air quality and biodiversity as well as promote recreation/aesthetic benefits (Albert et al., 2019; EC, 2021a).

Thus, NBS provide several environmental, social and economic benefits and co-benefits, as they have the ability to provide multiple ecosystem services while mitigating urbanization and climate change impacts (Remme et al., 2024). Nevertheless, the strength of the concept relies on social benefits, as NBS can uphold aesthetic values, create recreational spaces, and increase natural area connectivity and accessibility, control land conversion, promote citizen engagement, inclusion and awareness, and improve mental and physical health. Moreover, NBS reduce the number of people impacted and economic losses from natural disasters, increase land and property values as well as economic opportunities while, also, promoting environmental justice and urban regeneration (EC, 2015, 2021b; Faivre et al., 2017). There are, however, also disservices that have to be addressed in order to reach full potential and acceptance of NBS by citizens and policymakers (Pereira & Baró, 2022), such as gentrification, high costs, allergies, root damage and littering (see Pereira et al., 2023). To identify, assess and value the multiple ecosystem services and disservices provided by NBS across stakeholders in urban landscapes, stakeholder engagement is considered essential (see e.g. McPhearson et al., 2018; Remme et al., 2024).

Several barriers to NBS implementation are recognized, such as limited evidence on the impacts, costs and benefits, required implementation and maintenance effort, institutional and financial constraints, stakeholders awareness and engagement, replicability and planning issues related to each city uniqueness (Kabisch et al., 2022; López-Maciel et al., 2023; Restemeyer & Boogaard, 2021; Reynolds et al., 2017; Voskamp et al., 2021). Policy instruments are recognized as effective tools to address these challenges (Mendonça et al. (2021a)). From a planning perspective, policy instruments can be formal, including laws, prohibitions and economic instruments, or informal, such as planning and strategic documents. In addition, co-creation processes and tools, such as workshops, interviews, surveys and model simulation tools, increase citizen and decision makers awareness and engagement that are key to promote the adoption and diffusion of NBS (see e.g. Adegun et al., 2021; Albert et al., 2019; De Los Rios-White et al., 2020).

Despite the multiple NBS socio-economic benefits and co-benefits as well as the importance of stakeholder acceptance and economic feasibility, most NBS impact assessment studies focus on environmental impacts, mainly related to flooding, temperature or air quality (see Faivre et al., 2017; Lafortezza et al., 2018; Liu et al., 2021). However, NBS also have the potential to act as amenities (or disamenities) and, thus, influence housing location (see Mendonça et al., 2021b), property values (see Bockarjova et al., 2020), gentrification (see Wolch et al., 2014), urban form (see Cortinovis et al., 2022) and overall well-being (see Kooijman et al., 2021). This feeds the need for multi-perspective assessments to facilitate decision-making processes (see Liu et al., 2021), and development of an evidence base on environmental- and socio-economic benefits (see Lafortezza & Sanesi, 2019) as well as promoting engagement of stakeholders and decision-makers (EC, 2015).

Overall, there is a lack of studies that simultaneously assess the land use and socio-economic impacts of NBS, highlighting the need for a strong evidence-base and awareness promotion while cities try to balance several NBS benefits (Croeser et al., 2021; EC, 2021b; Joshi & Teller, 2021; Wang et al., 2025a). Considering the importance of co-creation that integrates stakeholders in NBS planning, adoption and diffusion (De Los Rios-White et al., 2020; EC, 2021b; Frantzeskaki, 2019), several authors use co-creation tools with municipalities, private sector and citizens, thus demonstrating their effectiveness in NBS co-creation and facilitating the decision-making process (e.g. Adegun et al., 2021; Badura et al., 2021; Devisscher et al., 2022; Langemeyer et al., 2020; McEwen et al., 2020; Venter et al., 2021). Considering the importance of modelling approaches that develop an evidence-base and ex-ante assessment of NBS benefits, obtaining estimated impact assessment results in less time and at lower costs (see Frantzeskaki et al., 2019; Liu et al., 2021; Mendonça et al., 2021b), there is a lack of spatially explicit simulation modelling approaches that assess the socio-economic impacts of NBS (see Mendonça et al., 2021b; Voskamp et al., 2021). To the best of our knowledge, no combination of co-creation and spatially explicit socio-economic modelling methodologies involving NBS were found, as literature mostly focuses on co-creation and environmental impacts modelling (EC, 2021a; Kabisch et al., 2022).

Hence, the objective of this study is to develop and apply an integrated approach that allows for the co-creation and socio-economic assessment of NBS scenarios. To this end, a NBS co-creation workshop procedure is developed (following Albert et al., 2019) and integrated with the spatially-explicit hedonic pricing simulation model SULD (see Roebeling et al., 2017), as to allow for the co-development, -assessment and -discussion of NBS scenarios. A case study is provided for the Municipality of Tampere (Finland), in the context of the H2020 UNaLab project (https://unalab.eu/en). This paper goes beyond previous studies by developing and applying an integrated co-creation and socio-economic assessment approach, which allows stakeholders to define and map urban challenges, explore and map possible NBS to address these challenges, and assess (ex-ante) the land use and socio-economic impacts of corresponding NBS scenarios. Hence, NBS can be co-created and assessed in a transparent, multi-stakeholder and participatory context and, in turn, systematically incorporated into urban landscape planning.

The remainder of this paper is structured as follows. The next section encompasses the methodology, including case study (Section 2.1), workshop (Section 2.2) and model (Section 2.3) descriptions. In turn, the results section includes the description of the baseline results

(Section 3.1) and the NBS scenario simulation results (Section 3.2). Finally, the discussion (Section 4) and conclusions (Section 5) are presented.

2. Methodology

This section presents the case study description for the city of Tampere in Finland (Section 2.1) as well as the methodology used, including the NBS co-creation workshop procedure (Section 2.2) and the SULD hedonic pricing simulation model (Section 2.3).

2.1. Case study description

Tampere is one of the larger inland cities within the Nordic countries and the third largest city in Finland. It has the second most populated urban area in the country and is one of the fastest growing territories and industrial centres, underlining the importance of planned urbanization and climate change mitigation. In addition, the development of new urban-residential and industrial spaces represents an opportunity to foster a more informed, sustainable and co-created planning process (EC, 2021b).

Key urban challenges in Tampere include flooding, water/air pollution, reduced biodiversity and rapid growth/increasing densification. In fact, through the UNaLab Project, the city has already implemented some NBS (retention pond, biofilter and alluvial meadows) targeting primarily flooding and water quality in its lakes to mitigate the pollution impact of rapid urbanization. Despite the large amount of green and blue spaces as well as the focus on water quality and biodiversity, the city intends to implement more NBS and acknowledges densification as an essential concern for its development, aiming to foster wellbeing and cohesion (EC, 2021b). According to surveys carried out in Tampere and Finland, residents already recognize the recreational and attractiveness value of NBS (EC, 2021b; Mesimäki et al., 2019).

2.2. NBS co-creation workshop

The present methodology is in line with Albert et al., (2019) conceptual framework for NBS implementation, including co-creation with stakeholders, benefits present in literature discussion, creation of scenarios and impact assessment. The selection of NBS scenarios together with stakeholders increases their awareness and allows them to identify those NBS that they perceive as capable of targeting their specific urban concerns. After the impact assessment, results were shared with stakeholders during project meetings – thus facilitating NBS implementation success and the decision-making process (Croeser et al., 2021; Voskamp et al., 2021). For a review of participatory modelling methods for sustainable transitions, please refer to Moallemi et al. (2021).

The first part of the methodology includes the NBS co-creation workshop, held on 27th of March 2020, via Microsoft Teams due to the pandemic restrictions. The participants (7) from the Municipality of Tampere, included people from different departments, such as urban planning, infrastructure development, green space management, water management and biodiversity management, that are representative of the different stakeholders in the area. The first part of the workshop included the case study area definition and problem identification. The online UMap tool (https://umap.openstreetmap.fr/en) was used to allow sharing, editing and drawing on maps by workshop participants. The chosen case study area was the city centre of Tampere, where the main urban problems identified include flood risk and water pollution, air pollution, noise, lack of green space and habitat loss, and densification and liveability issues (see Fig. 1a for the problem identification map).

Following the problem identification, the NBS mapping phase started by presenting a list of possible NBS and their expected impacts and benefits (following EC, (2021b)). Several NBS were selected that have the ability to target the previously identified urban problems, including green roofs, city/street trees, green spaces, biofilters, river daylighting and bio-swales (see Fig. 1b for the NBS mapping). NBS scenarios considered in this study include green roofs, street trees and river daylighting; bio-swales were not considered in this study because there is no evidence in literature that bio-swales provide socio-economic benefits other than flood mitigation benefits.

Finally, the workshop participants classified the existing green/blue spaces and the short-listed NBS by level of attractiveness (following Roebeling et al., 2017): highly attractive urban amenities (type 1); medium attractive neighbourhood amenities (type 2); and low attractive local amenities (type 3). This qualitative characterization, based on green/blue space size, degree of landscaping and recreation possibilities, was used in the model to assess the influence sphere of these environmental amenities – namely the rate of decrease in amenity level as one moves away from the environmental amenity (see Section 2.3).

2.3. SULD hedonic pricing simulation model

After the NBS scenarios were co-created, the corresponding socio-economic impacts were assessed using the Sustainable Urbanizing Landscape Development (SULD) model (see Roebeling et al., 2007, 2017). SULD is a spatially explicit hedonic pricing simulation model that determines the location of residential development and densities, real estate values and living space for different household types, depending on household characteristics, construction costs, and proximity to environmental amenities and urban centres. It has previously been used

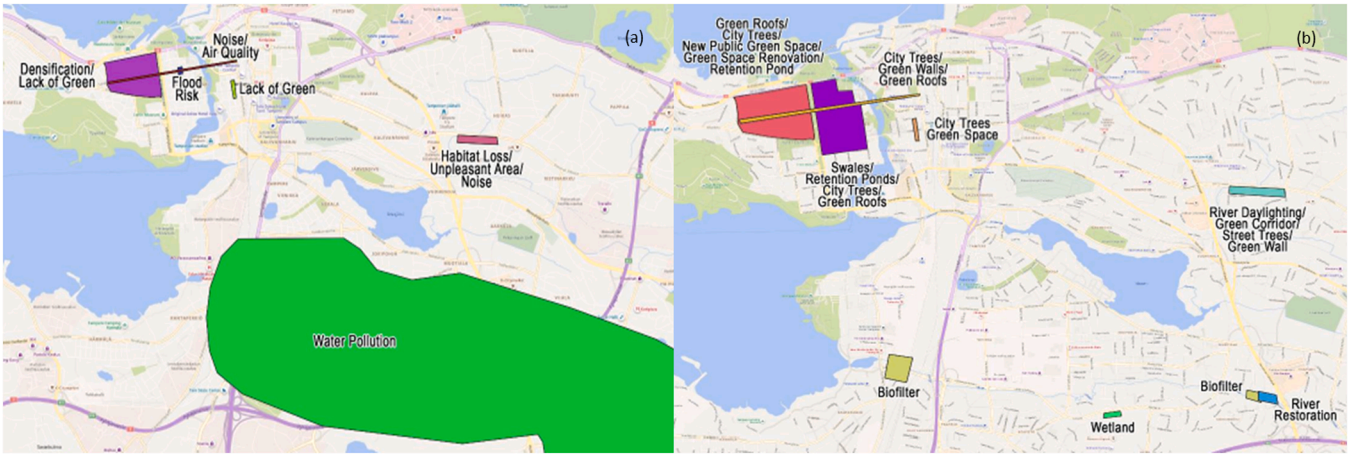

Fig. 1. NBS co-creation workshop maps: a) problem identification and b) NBS mapping.

to assess the socio-economic impacts of urban population growth and residential development (Roebeling et al., 2007), green/blue space and infrastructure development (Roebeling et al., 2017), urban population decline (Saraiva et al., 2017) and policy instruments to steer urban residential sprawl (Mendonça et al., 2020).

SULD is a general equilibrium model in which the demand side represents households that aim to maximize their utility U, at each location i, from residential space S, other goods and services Z, and environmental amenities e, subject to their income y (budget) constraint:

$$\underset{S_i,Z_i}{Max} U_i(S_i, Z_i) = S_i^{\mu} Z_i^{(1-\mu)} e_i^{\varepsilon} \quad (1)$$

$$\text{subject to } y = p_i^h S_i + Z_i + p_x x_i$$

and where μ is the elasticity of demand for residential space (S_i) and ε is the elasticity of utility with respect to environmental amenities (e), and where p^h is the rental price of housing, p_x are commuting costs and x_i is the road-network distance to the nearest urban centre (see Fig. 2). The environmental amenity level e that households obtain, at each location i, is decreasing with distance from the environmental amenity:

$$e_i = 1 + \sum_q \alpha_q \cdot \exp^{-\beta z_{iq}} \quad (2)$$

where α_q is the level of amenity provided by the environmental amenity of quality q, β is the rate of decrease in level of amenity with distance from the environmental amenity, and z_q is the Euclidean distance from location i to the nearest environmental amenity of quality q.

The supply side represents real-estate developers that aim to maximize their profits π, at each location i, from housing construction revenue ($p^h D$) net of housing development costs ($l+D^{\eta}$):

$$\underset{D_i}{Max} \pi_i(D_i) = p_i^h D_i - (l_i + D_i^{\eta}) \quad (3)$$

$$\text{with } D_i = n_i S_i$$

and where D is the development density, l is the opportunity cost of land, D^{η} is the construction cost function and η is the ratio of housing value to non-land construction costs, and where n is the household density.

In equilibrium, the demand for housing equals the supply of housing and, at each location i, the equilibrium land rent price r and household density n are derived:

$$r_i = \left(\frac{k e_i^{\varepsilon} [y - p_x x_i]}{u} \right)^{\frac{\eta}{\mu(\eta-1)}} \quad (4)$$

$$n_i = \frac{D_i}{S_i} \quad (5)$$

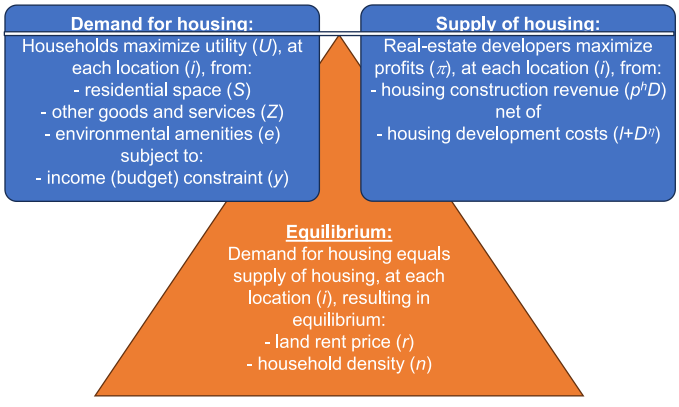

Fig. 2. Schematic presentation of the Sustainable Urbanizing Landscape Development (SULD) model.

with $k = (\mu m)^{\mu}(1-\mu)^{(1-\mu)}$ and $m = [(\eta-1)^{(\eta-1)/\eta}]/\eta$. For the full derivation of the model, please refer to Roebeling et al. (2007, 2017).

The rationale underpinning the NBS scenario simulation results is as follows. NBS increase environmental amenities (e) in surrounding locations (i). This leads to an increase in equilibrium land rent price (r; see Eq. 4). Given their income (budget) constraint (y; Eq. 1), households need to respond to this increase in the rental price of housing by: i) reducing residential space (S), ii) reducing consumption of other goods and services (Z) and/or iii) reducing environmental amenities (e) by moving away from them. Depending on the quality and size of as well as distance to the NBS, households currently living near the NBS respond and are, either-or-not / to a smaller or larger extent, bought-out by higher-income households in each location (i).

SULD has been developed and applied to the city of Tampere, with socio-economic data provided by the Municipality of Tampere and from local statistics sources (Tilastokeskus; Municipality of Tampere 2018), while land use data was retrieved from the Urban Atlas (Urban Atlas, 2018) and, in turn, calibrated and validated (following Saraiva et al., (2017)). Parameterization values are based on three different household types (HH types; following Roebeling et al., 2017): low-income households (HH type 1) represent 31% of the population that earn 9% of the total income; middle-income households (HH type 2) represent 46% of the population that earn 44% of the total income; and high-income households (HH type 3) represent 23% of the population that earn 47% of the total income (see Table 1). Environmental amenities (urban green/blue spaces and NBS) are divided in three levels of attractiveness (following Roebeling et al., 2017): highly attractive urban amenities, including water (type 1); medium attractive neighbourhood amenities (type 2); and low attractive local amenities (type 3); appreciation for environmental amenities is equal across household types and reflects exponential distance decay ($\varepsilon = 0.08$; $\alpha = 10.0$; $\beta = 1.0$). Accordingly, there is a housing location decay function based on straight-line distance to the nearest amenity as well as road distance to the nearest urban centre. Urban centres include city centres, business districts, hospitals, schools, universities, shopping malls and train stations. See Fig. 3a for the distribution and location of environmental amenities and urban centres. In addition, annual transport costs considered were 278€/Km (Municipality of Tampere, 2018), opportunity cost of land 2250€/ha/year (Municipality of Tampere, 2018) and construction costs 2250€/m^2 (Municipality of Tampere, 2018).

Regarding the case study area, the city centre and periphery was covered, using ArcGis software, with a 185 by 185 grid layer of 34 m by 34 m (34225 cells corresponding to a total area of 1156 m^2). Model calibration included levels of utility $u = 2525$ for HH type 1; $u = 5949$ for HH type 2; $u = 12001$ for HH type 3), being validated through a comparison of observed and simulated housing prices, living spaces and land uses. For the latter, the base scenario maps were confronted with the most recent land use maps from the Urban Atlas, adopting location and quantity disagreement indicators (Pontius et al., 2004; Saraiva et al., 2017). Calibration results indicate that the amount of residential cells is underestimated by 10% (quantity disagreement) and that the location of land use cells is correct in 89% of the times, while urban cells accuracy accounts for 60% (location agreement), as low density urban

Table 1
Household characteristics for the Tampere case study area (based on: Municipality of Tampere, 2018).

	Unit	HH type 1	HH type 2	HH type 3	Total
Population	#	61 387	90 291	40 013	191 691
HH size	#/hh	1.7	1.7	1.7	1.7
Households	#	36 110	53 112	23 537	112 759
Expendable income	€/year	8 125	26 531	59 326	309.9×10^7
Housing expenditures	%	27%	25.9%	25.4%	26.1%

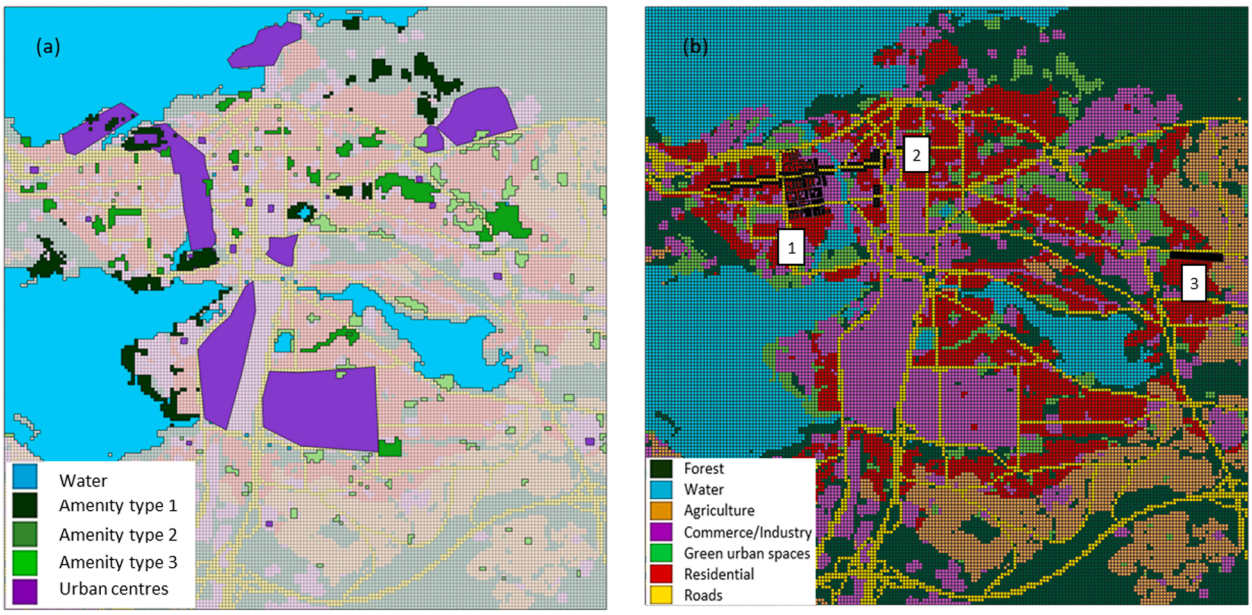

Fig. 3. Spatial distribution of Tampere (a) environmental amenities types (1 = dark green, 2 = medium green, and 3 = light green) and urban centres (purple); and (b) land use and NBS scenarios in black (1- Green roofs; 2- Street trees; 3- River daylighting).

areas (mainly located in the periphery) were considered agricultural in the baseline while regarded as residential in the original land use map. The validated and calibrated results were then used to simulate green roofs (scenario 1; 12 ha), street trees (scenario 2; 15 ha) and river daylighting (scenario 3; 4 ha) – see Fig. 3b. Green roofs and street trees were considered by the workshop participants as being type 3 environmental amenities given the limited attractiveness (namely small usable size and limited recreation possibilities), while river daylighting was modelled as a type 1 environmental amenity given the high attractiveness of green/blue spaces (large usable size, degree of

Table 2
Baseline and NBS scenario simulation results at city level.

Land use	Baseline	Green roofs (Scen. 1)	%	Street trees (Scen. 2)	%	River daylighting (Scen. 3)	%
Forest (ha)	866	866	0.0%	866	0.0%	866	0.0%
Water (ha)	730	730	0.0%	730	0.0%	730	0.0%
Agriculture (ha)	826	818	−1.1%	811	−1.8%	828	0.3%
Industry/Commerce (ha)	680	680	0.0%	680	0.0%	680	0.0%
Green urban spaces (ha)	201	201	0.0%	215	6.9%	206	2.4%
Roads (ha)	378	378	0.0%	378	0.0%	378	0.0%
Urban (ha)							
Res1 (ha)	54	54	−0.5%	54	−0.3%	54	−0.3%
Res2 (ha)	125	130	3.9%	126	0.3%	123	−1.8%
Res3 (ha)	95	99	4.4%	96	1.0%	90	−4.8%
Total (ha)	275	283	3.2%	276	0.4%	268	−2.5%
Total (ha)	3956	3956	0.0%	3956	0.0%	3956	0.0%
Housing quantity							
Res1 (1000 m^2)	123.9	123.3	−0.5%	123.5	−0.3%	123.5	−0.4%
Res2 (1000 m^2)	754.6	792.4	5.0%	757.9	0.4%	736.5	−2.4%
Res3 (1000 m^2)	1146.0	1208.8	5.5%	1159.9	1.2%	1076.8	−6.0%
Total (1000 m^2)	2024.6	2124.5	4.9%	2041.4	0.8%	1936.8	−4.3%
Living space							
Res1 (m^2/hh)	109.2	109.1	−0.2%	109.1	−0.2%	109.2	0.0%
Res2 (m^2/hh)	288.6	291.0	0.8%	288.7	0.0%	287.4	−0.4%
Res3 (m^2/hh)	582.2	587.8	1.0%	583.4	0.2%	575.5	−1.1%
Average (m^2/hh)	298.4	300.7	0.8%	298.6	0.1%	296.3	−0.7%
Real estate value							
Res1 (€/m^2/yr)	19.6	19.6	0.1%	19.6	0.0%	19.6	0.1%
Res2 (€/m^2/yr)	23.3	23.1	−1.0%	23.3	−0.1%	23.4	0.5%
Res3 (€/m^2/yr)	25.5	25.2	−1.1%	25.4	−0.3%	25.8	1.3%
Average (€/m^2/yr)	23.3	23.1	−0.7%	23.3	−0.1%	23.5	0.6%
Total (m€/yr)	818.3	816.9	−0.2%	817.7	−0.1%	819.3	0.1%
Distance to amenity							
Type 1 (m)	562.3	562.3	0.0%	562.3	0.0%	529.0	−5.9%
Type 2 (m)	750.7	750.7	0.0%	750.7	0.0%	750.7	0.0%
Type 3 (m)	438.4	415.4	−5.2%	426.9	−2.6%	438.4	0.0%
Ratio of open space to build form (#)	1.31	1.28	−2.1%	1.29	−1.2%	1.32	1.3%
Percent built-up area (%)	43.3	43.9	1.2%	43.6	0.7%	43.0	−0.7%

Note:[1] Res1 = Low-income households; Res2 = Middle-income households; Res3 = High-income households.
[2] Amenity type 1 = high attractiveness (urban); Amenity type 2 = medium attractiveness (neighbourhood); Amenity type 3 = low attractiveness (local).

landscaping and recreation possibilities; see Fig. 3a).

3. Results

This section presents the baseline (Section 4.1) and scenario simulation results (Section 4.2) to assess the impact of green roofs, street trees and river daylighting implementation in Tampere at the city (Table 2) and local level (Fig. 4).

3.1. Baseline results

The Baseline scenario simulation results (Fig. 4 and Table 2) show that the majority of land use in Tampere is forest (866 ha; 22%), agriculture (826 ha; 21%) and water (730 ha; 19%), followed by industry and commerce (680 ha; 17%), residential (275 ha; 7%) and urban green spaces (201 ha; 5%). Regarding residential land use, middle-income households (Res2) take-up the largest area (125 ha or 46%), as they also represent the largest share of households (47%), followed by high-income households (Res3: 95 ha or 35%; 21% of households) and low-income households (Res1: 54 ha or 20%; 32% of households). As for the housing quantity (square meters of built area), however, high-income households take up the largest area ($1146*10^3$ m^2), followed by middle-income households ($754*10^3$ m^2) and low-income households ($123*10^3$ m^2). This is in line with living space, which varies between 582 m^2 for high-income households to 109 m^2 for low-income households. Real estate (rental) values are highest for high-income households (26 €/m^2/yr) and lowest for low-income households (20 €/m^2/yr), resulting in an average real estate value of 23 €/m^2/yr. Real estate values are higher near environmental amenities, especially type 1 (see Figs. 3 and 4; up to 28 €/m^2/yr), where higher income households (Res2 and Res3) are located and household density is lower. Given the ample availability of environmental amenities, high-income households

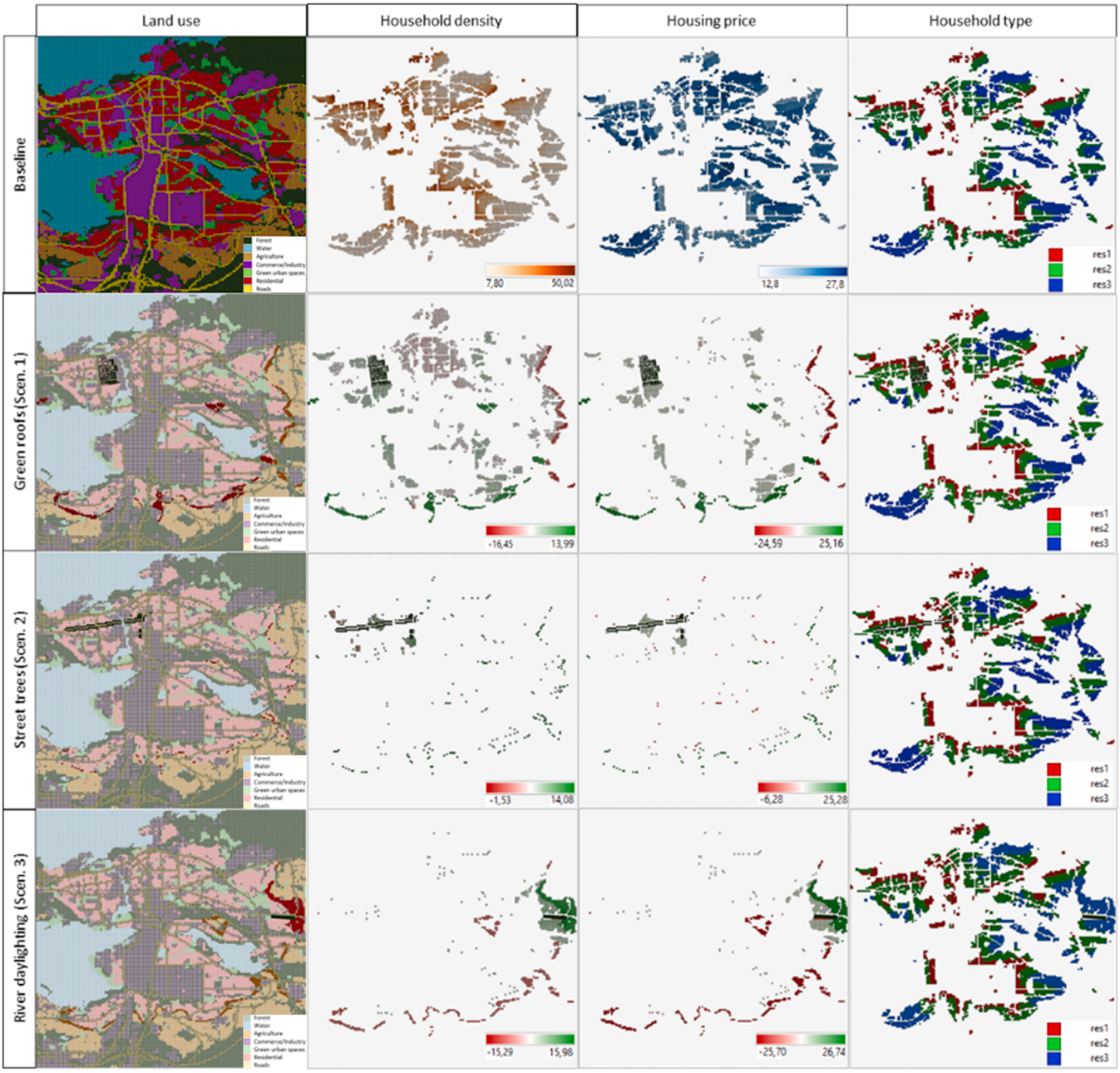

Fig. 4. Baseline and NBS scenario simulation results, with land use, household density and housing price difference maps and household type maps.

locate on more peripheral areas where they can afford bigger houses and enjoy lower population density. Real estate values are lower near urban centres and main roads (around 14 €/m^2/yr), where low-income households settle. The total real estate (rental) value for the Tampere study area is around 818 m€/yr. The average distance to the nearest amenity varies between 438 m to amenity type 3, 750 m to amenity type 2 and 562 m to amenity type 1. The ratio of open space to build form is 1.31 and the percent built-up area is 43.3%.

3.2. Scenario simulation results

The objective of this study is to assess the socio-economic and land use impacts of three different NBS scenarios (green roofs; street trees; river daylighting) in the city of Tampere. To promote a more sustainable development, it is expected that the city becomes more compact, increasing non-built land use types. Hence, living spaces and housing quantity are expected to decrease while household density and housing prices are expected to increase with the implementation of new attractive environmental amenities. Regarding environmental related indicators, a higher share of green urban spaces is foreseeable, with a reduction in respective distances to environmental amenities and of built-up areas. From a social perspective, the household type changes can provide insights in segregation patterns.

The implementation of green roofs (Scenario 1) leads to an overall increase in urban residential area (+8 ha or +3.2%) and, hence, a decrease in agriculture area (−8 ha or −1.1%; see Fig. 4 and Table 2). The low attractive green roofs (environmental amenity type 3) result in small increase in low-income household (Res1) density in/near the green roofs implementation area and, associated, overall negligible decrease in housing quantity (−0.5%) and living space (−0.2%). This local contraction results in a decrease in population density and real-estate values, namely, to the south of the green roofs implementation area. As a result, middle-income (Res2) and high-income (Res3) households from the eastern periphery – having similar access to environmental amenities and increased access to urban centres (see Fig. 3) – are able to afford larger living spaces at a lower cost, relocating and expanding to the southern periphery of the urban area (with, respectively, a 3.9% and 4.4% increase in residential area). With the green roofs being implemented in an area where lower-income households already live, there is no significant change in household type distribution (Fig. 4). Accordingly, housing quantity decreases by 0.5% for low-income households in/near the green roofs implementation area and urban centres, and increases by around 5% for the middle and high-income households in peripheral areas, with an overall average increase of 5%. Living space remains essentially the same for low-income households (−0.2%), while middle- and high-income households increase their living space (both around +1%) as they prefer to expand to less dense locations on the southern periphery. In/near the green roofs implementation area, real estate (rental) values increase slightly (by up to 2%) and reflect the lower-income households' willingness to pay to live in/near houses with green roofs. Overall, at the city level, differences in real estate values are negligible for low-income households (+0.1%) and minor for middle and high-income households (around −1%) – resulting in an overall negligible decrease in total real estate (rental) value of 0.2%. The implementation of green roofs (environmental amenity type 3) represents an average decrease of 5.2% in overall distance of households to low attractive local environmental amenities (type 3). With the urban expansion, the ratio of open space to build form decreases by around 2% and the percent built up area increases by 1.2%.

The implementation of street trees (Scenario 2), the impact on the overall urban form and namely on urban residential area is virtually none (1 ha or 0.4%). Agricultural area suffers a more visible decrease (−15 ha or −1.8%) due to the new implementation area conversion (Fig. 4 and Table 2). The slight expansion of the urban area follows a similar but softer pattern to scenario 1 implementation, with a negligible expansion of higher-income households in the peripheral area (0.3% for Res2 and 1% for Res3). Conversely, low-income households experience a close to null contraction around the street trees implementation, as they are willing to pay slightly more and reduce their living space to live near the NBS area (−0.3%, see Table 2). This results in a small decrease in population density and real estate values around the street trees implementation area. Consequently, middle-income and especially high-income households are able to afford equal or slightly larger living spaces in less dense areas at a lower cost without compromising access to amenities, and increasing access to urban centres, hence slightly expanding to more peripheral areas. Once again, no visible alteration of the household type distribution pattern accrues from the NBS implementation, as lower-income households already lived near the implementation area (Fig. 4). Hence, housing quantities reduces for low-income households near the street trees implementation area (−0.3%) and increases for middle and high-income groups in the periphery of the urban area (0.4% and 1.2%, respectively), with an overall increase of 0.8%. In accordance, living space suffers virtually no changes (0.1% increase on average), with a −0.2% decrease for low-income households near the street trees implementation area. No alteration was visible for middle-income households and living space slightly increases for high-income households (0.3%), as they prefer to live in less dense locations in peripheral areas. In the street trees implementation area, real estate values increase up to 3.2% as lower income households are willing to pay slightly more to live closer to locations that are more attractive. However, on average, at city level, differences in real estate value are virtually none, with no changes for low-income households and small decreases for middle- and high-income households (−0.2% and −0.3%, respectively) with a total decrease of −0.1%. The implementation of street trees (amenity type 3) leads to a decrease of the overall distance of households to amenity type 3 of −2.6%. With the small urban expansion, the ratio of open space to build form decreases −1.2% and the percent built up area increases 0.7%.

Finally, the implementation of river daylighting (Scenario 3) results in a contraction of the urban area due to high-income households moving to the area surrounding the highly attractive NBS. The urban residential area decreases by 2.5%, influencing mostly high-income households (−4.8%), followed by middle (−1.8%) and low-income households (−0.3%), with a corresponding increase of 0.3% in agriculture area (see Table 2 and Fig. 4). High-income households relocate to the unoccupied areas surrounding the river daylighting implementation area, being willing to pay more to live in this more attractive area even at the expense of smaller living spaces and higher household densities. The lower-income households follow the same pattern, even if slightly, contracting and relocating in the direction of the river daylighting implementation area (Fig. 4). The household distribution pattern is hardly affected as lower-income households (Res1 and Res2) cannot compete with the high-income households (Res3) to live near the river daylighting implementation area, where the higher-income households were already living. Hence, housing quantity decreases (−4.3%), mainly for high-income households (−6%) followed by middle- and low-income households (−2.4% and −0.4%, respectively). As households are willing to live in somewhat smaller and more densely populated areas near the new attractive river daylighting area, living space shows a small overall reduction of almost 1% - namely for high-income households (−1.1%) and middle-income households (−0.4%). Real estate (rental) values increase up to around 26 €/m^2/yr (+24.1%) near the river daylighting area, as a result of the increasing demand for housing by, in particular, high-income households. Overall, at the city level, real estate values increase by between 0.1% for low-income households to 1.3% for high-income households – resulting in an increase in total real-estate value of 0.1%. River daylighting (environmental amenity type 1) decreases households' distance to highly attractive urban amenities (type 1) by 5.9%. Unlike the other two NBS scenarios, river daylighting leads to an increase of 1.3% in the ratio of open space to build form and a decrease of 0.7% in the percent built-up

area.

4. Discussion

Using an integrated approach that allows for the integrated co-creation and socio-economic assessment of NBS scenarios, this study assessed the land use and socio-economic impacts of co-created green roofs (Scenario 1), street trees (Scenario 2) and river daylighting (Scenario 3) scenarios in the city of Tampere (Finland). This study goes beyond previous green roofs, street trees and river daylighting assessment studies in several ways:

- For green roofs, most studies assess air quality (Anderson et al., 2021; Ascenso et al., 2021), flooding (Basu et al., 2021; Costa et al., 2021; Wang et al., 2025a), and temperature reduction/building cooling (Anderson & Gough, 2022; Coma et al., 2020; Marvuglia et al., 2020). As for land use and socio-economic impacts, green roofs can be considered amenities, promoting recreational benefits, social cohesion well-being and influencing property values, depending on the urban form, income, distance, usability and accessibility (Adegun et al., 2021; Cortinovis et al., 2022; Langemeyer et al., 2020; Pereira & Baró, 2022; Venter et al., 2021). However, most studies are theoretical (Adegun et al., 2021; Liu et al., 2021; Pereira & Baró, 2022; Teotónio et al., 2021) or only include surveys or workshops (Langemeyer et al., 2020; Mesimäki et al., 2019; Sarwar & Alsaggaf, 2020; Venter et al., 2021). No study was found that combined co-creation methods with simulation (Langemeyer et al., 2020; Sarwar & Alsaggaf, 2020).
- For street trees, the majority of studies assess temperature reduction (Cortinovis et al., 2022; Marando et al., 2019) and air quality (Anderson et al., 2021; Reynolds et al., 2017). Street trees have recreational benefits, improve accessibility to green spaces, promote well-being and have the potential to steer land management, depending on the area planted (Adegun et al., 2021; Reynolds et al., 2017). Again, studies were theoretical (Adegun et al., 2021) or GIS mapping (Acosta & Haroon, 2021; Reynolds et al., 2017). In fact, no study was found joining co-creation and simulation, highlighting the potential for socio-economic assessments, in line with EC (2020).
- For river daylighting, assessment studies are scarce and theoretical. Most studies include other water-related NBS, such as bio-swales and retention ponds, that are mostly focused on flood control and heat mitigation though not on cultural and socio-economic impacts (Antoszewski et al., 2020). However, rivers and other blue spaces are recognized to be highly attractive, promote well-being and provide recreational potential in cities (Albert et al., 2019; EC, 2015; Lafortezza & Sanesi, 2019).

The developed and applied integrated co-creation and socio-economic assessment approach allows stakeholders to co-define and map urban challenges, co-explore and map possible NBS to address these challenges, and co-assess (ex-ante) the land use and socio-economic impacts of corresponding NBS scenarios (following De Los Rios-White et al., 2020). Sustainable urban planning requires decision-making that acknowledges the complex interactions between environment, community and economy, thereby building on scientific knowledge to inform stakeholders in the decision-making process (Bohnet et al., 2011). The developed approach facilitates urban planners' participatory planning and public discussion, by improving stakeholders' awareness about key common urban challenges, feasible nature-based solutions, and corresponding complex land use and socio-economic impacts.

The implementation of green roofs in the centre of Tampere did not pose the expected impact of that of a new attractive environmental amenity, as it even caused a small expansion of the urban area, somewhat increasing land conversion and urban sprawl. Nevertheless, there was a slight densification of low-income households in/near the green roof implementation area where they already lived (i.e. minor socio-spatial displacements), highlighting a small and local attraction potential from green roofs while not contributing to gentrification. Hence, green roofs only had a small positive impact on the urban pattern near the implementation area, which is also supported by literature, stating that the demand for green roofs is higher in more dense and central locations with, usually, less green areas (Williams et al., 2021). The overall large share of green/blue spaces in Tampere (almost 50%), thus, also explains the relatively small impact of green roofs. In addition, cultural values are not the main green roof benefits (Langemeyer et al., 2020; Sarwar & Alsaggaf, 2020; Snep et al., 2020). Adegun et al. (2021), Cortinovis et al., (2022) and Langemeyer et al., (2020) did not find any significant social benefits from green roofs implementation, as they only provided benefits to households in/near the green roof implementation area and they also add little greenness. In addition, McClymont et al., (2020) and Venter et al., (2021) also found that green roofs did not have a high amenity value, with limited attractiveness, especially without accessibility. Furthermore, green roof benefits are dependent on location and can be less attractive for some household types (see e.g. Joshi & Teller (2021) and Williams et al., (2021)). According to a survey in Finland (Mesimäki et al., 2019), however, green roofs are acknowledged to have cultural benefits – dependent on scale and size (Anderson et al., 2021; Frantzeskaki, 2019). Comprehensively, green roofs have small potential to influence urban patterns while their socio-economic benefits are dependent on accessibility, size, location and existing green/blue space (Cortinovis et al., 2022; Frantzeskaki, 2019; Kabisch et al., 2022).

Regarding the street trees scenario in the central area of Tampere, the overall impact was virtually non-existent – with a small urban expansion that followed a similar but softer trend as the green roof scenario. Lower income households that already lived near the street trees implementation area slightly densified, increasing property prices and household density as households are willing to live in smaller spaces. This created a slight decrease in housing demand in the remaining urban area, allowing few higher-income households to maintain their access to attractive amenities and slightly expand, living in larger, less expensive and dense areas. Thus, the impact of street trees, also considered a low-attractive environmental amenity, had a slight positive impact locally on low-income households that do not have to compete with other income groups in the implementation area (i.e. minor socio-spatial displacements) and, hence, did not contribute to gentrification. These results are supported by literature, as street trees are recognized to have a greater potential when implemented in high-density and central areas, while noting that accessibility is considered important in NBS cultural impact (Arthur and Hack, 2022). Hence, street trees only had a very small positive impact on the urban pattern near the implementation area, explained by the relatively low attractiveness of the NBS, the already abundant green/blue spaces in Tampere and the relatively small implementation area, not contributing much to the urban greenness. The latter is considered key by several authors in determining street trees' land patterns benefits (Acosta & Haroon, 2021; Badura et al., 2021; Marando et al., 2019; Reynolds et al., 2017).

The river daylighting scenario had an opposite and more beneficial impact on land use and socio-economic dynamics in Tampere, leading to a reduction in urban residential area and, thus, increasing urban compactness with the implementation of the new attractive NBS. Living space and housing quantity reduced for all household types, while household density and housing prices increased. Accordingly, high-income households were the most impacted, followed by middle and low-income households. In fact, higher-income households already lived near the river daylighting implementation area, moving even more towards the attractive NBS without having to buy-out other households (i.e. minor socio-spatial displacements) and, thus, also this NBS did not contribute to gentrification. Lower income households follow the same trend, even if less impacted, and contract in the direction of the river daylighting implementation area. These results reinforce the importance

of NBS attractiveness (i.e. quality of the environmental amenity) on socio-economic and land use pattern impacts, as stated by several authors (Frantzeskaki, 2019; McClymont et al., 2020; Teotónio et al., 2021). The high attractiveness proved to be more important than NBS size, as the river daylighting was the smaller intervention simulated. In fact, the attractiveness value associated with water NBS is acknowledged in literature, having a crucial role in promoting citizens connection with rivers (EC, 2021a; Frantzeskaki, 2019; McEwen et al., 2020). Moreover, the latter authors found that river daylighting has a significant impact on social, environmental and cultural aspects of a city, supporting the results of this study. Overall, this study is also in line with Roebeling et al. (2017), Lafortezza et al., (2018) and Mendonça et al., (2021b) findings, that show NBS can have positive socio-economic and land use impacts, such as controlling urban sprawl, increasing property prices and promoting household density, even in relatively green cities.

Thus, results show that the implementation of NBS does have socio-economic impacts, namely on housing prices, household density and living space as well as urban form/sprawl, as widely acknowledged in literature (Adegun et al., 2021; EC, 2015; Langemeyer et al., 2020; Mendonça et al., 2021b). In addition, it is shown that attractiveness, size and accessibility to nature-based solutions (environmental amenities) is key in defining urban shape and housing development patterns (EC, 2015; Roebeling et al., 2017; Mendonça et al., 2020; Teotónio et al., 2021). Overall, despite being considered a consequence of land conversion, NBS implementation did not contribute to further household gentrification, even if different households were impacted distinctly (as stated by Sarwar & Alsaggaf, (2020)). In fact, distribution patterns did not suffer significant changes in any of the NBS scenarios (i.e. minor socio-spatial displacements), because the most attractive NBS was implemented in an area where higher-income households lived (river daylighting) and less attractive NBS were implemented in areas where lower-income households lived (green roofs; street trees). Consequently, high-income households continue to live in peripheral areas near highly attractive environmental amenities, low-income households near urban centres and middle-income households in between (in line with Roebeling et al., (2017) and Mendonça et al., (2020)).

5. Conclusions

An integrated approach that allows for the co-creation and socio-economic assessment of NBS scenarios was developed, integrating a NBS co-creation workshop procedure and a spatially-explicit hedonic pricing simulation model, as to allow for the co-development, -assessment and -discussion of NBS scenarios for the case of Tampere (Finland). This study contributes to the knowledge base regarding land use and socio-economic impact assessment of NBS, integrating stakeholder engagement and scenario simulation approaches that are identified as scarce in literature (Lafortezza & Sanesi, 2019; Liu et al., 2021). The approach allows stakeholders to define and map urban challenges, explore and map corresponding NBS, and assess (ex-ante) resulting land use and socio-economic impacts. Hence, NBS can be co-created and assessed in a transparent, multi-stakeholder and participatory context, by improving stakeholders' awareness about the land use and socio-economic impacts of NBS – enriching public discussion, adding transparency and increasing public benefits. These are acknowledged to improve the NBS implementation success and to support more informed decision-making processes (EEA, 2016; Mendonça et al., 2021a).

NBS have an impact on land use patterns and socio-economic dynamics, however this study demonstrated that the impact can be positive or negative. In fact, low attractive NBS scenarios (namely green roofs and street trees) led to a local densification and increase in real-estate values though overall to a small expansion of the urban area and slight decrease in real-estate values. Contrarily, the high attractive NBS scenario (river daylighting) promoted an overall urban compactness with increasing household density and housing prices. Even though only the river daylighting scenario had the overall expected results, both the green roofs and the street trees scenarios had locally positive impacts. These results accentuate the importance of integrating co-creation (as an awareness raising and stakeholder engagement method) and modelling (as an ex-ante assessment tool) to facilitate the urban planning process, to create a strong evidence-base and to evaluate expected land use and socio-economic impacts of different NBS locations and sizes to different household groups and to control segregation patterns (EEA, 2016).

Summing up, NBS effectiveness demonstrated to be especially dependent on the attractiveness level but also on the size and accessibility as well as on pre-existing green conditions (Costa et al., 2021; Frantzeskaki, 2019). Additionally, NBS can generate a wide range of urban benefits for all households at different levels, but each city's physical and socio-economic structures uniqueness might condition the outcomes (Kabisch et al., 2022; Kooijman et al., 2021). In this case, the considerable share of attractive pre-existing green/blue amenities contributed to the little impact of low attractive NBS, only having a positive impact with high attractive NBS. With all the simulated scenarios, no visible extra segregation was fomented, as the spatial distribution of household types did not change. Nevertheless, no highly attractive NBS scenario was simulated in lower income household locations, which might influence segregation patterns and give further evidence on the location impact of NBS.

Overall, the model consistency was in line with previous studies (Mendonça et al., 2020; P. Roebeling et al., 2017; Saraiva et al., 2017), where compact cities show decreased housing quantity and living spaces, increased housing prices and household density as well as a decrease in distance to corresponding amenities. Nevertheless, some limitations exist. First, as relocations in real-life urban settings are costly, it may be considered to include transaction costs in the model as to avoid strong relocation impacts associated with small changes in scenarios. Accordingly, other developments might exist that counteract the simulated relocations, while policies or other factors could also have the possibility to address and steer these movements. Second, the co-creation workshop was held online at the start of the COVID−19 pandemic and, hence, availability and functionality of digital communication and collaboration platforms were still relatively limited. As a result, it was decided to work with participants from the Municipality of Tampere that were representative of the different stakeholders in the area (planning; infrastructure; green space; water resources; biodiversity) – under normal conditions it is preferable to organize such co-creation workshops in person with representatives of a broader group stakeholders. Third, future research should focus on additional NBS simulations in different urban settings to strengthen these conclusions, such as green roofs in less green cities, larger areas of street trees and high attractive NBS where low-income households live, to further understand the gentrification, inequalities and location potential. To this end, AI can be used to optimize urban green infrastructure effectiveness – thus improving the responsiveness, precision and scalability of NBS interventions (see e.g., Wang et al., 2025b). Moreover, policy instruments could be adopted to counteract some of the negative impacts and/or potentiate NBS benefits.

Concluding, simulated NBS demonstrated to have an impact on land use patterns and socio-economic dynamics, despite NBS effectiveness being dependent on its level of attractiveness, size and accessibility as well as conditioned by pre-existing quantity and quality of environmental amenities. Overall, green roofs had only local positive impacts, street trees had little impact and river daylighting led to an urban contraction. Hence, in urban areas with a larger green share, designed NBS should be more attractive to increase their land use and socio-economic benefits. NBS impacts are, consequently, case-dependent, highlighting the advantage of the present integrated methodology, including a co-creation approach to identify the urban problems and to explore NBS that may be considered to tackle them, alongside with simulation of corresponding NBS scenarios to facilitate an informed decision-making process and to promote more sustainable and inclusive

urban planning practices.

CRediT authorship contribution statement

Rita Mendonça: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Data curation, Conceptualization. **Peter Roebeling:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Funding acquisition, Formal analysis, Data curation. **Teresa Fidélis:** Writing – original draft, Supervision. **Miguel Saraiva:** Supervision, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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