

ARTICLE OPEN



Identifying where nature-based solutions can offer win-wins for carbon mitigation and biodiversity across knowledge systems

Christopher M. Raymond^{1,2,3}✉, Alex M. Lechner⁴, Minttu Havu⁵, Joel Jalkanen⁶, Jussi Lampinen^{1,3}, Oriol García Antúnez⁷, Anton Stahl Olafsson⁷, Natalie Gulsrud⁷, Antti Kinnunen⁸, Leif Backman⁹, Liisa Kulmala⁹ and Leena Järvi^{1,5}

Managing nature-based solutions (NBS) in urban areas for carbon mitigation and biodiversity outcomes is a global policy challenge, yet little is known about how to both assess and weave diverse knowledge systems and values into carbon-biodiversity trade-off assessments. This paper examines the spatial relationships between biophysical and social values for carbon sequestration potential (measured as carbon dioxide, CO₂, flux) and biodiversity in Helsinki, Finland, using integrated valuation. The approach combines methods from carbon sequestration modelling, expert scoring approaches to biodiversity assessment and public participation geographic information systems (PPGIS). Results indicate strong spatial associations between biophysical assessment of CO₂ flux and biodiversity priorities, and weaker associations between biophysical and social values. Integration of social and biophysical values leads to multiple pathways for protection of NBS to achieve carbon mitigation and biodiversity outcomes, as well as options for the spatial targeting of education and capacity building programs to areas of local concern.

npj Urban Sustainability (2023)3:27; <https://doi.org/10.1038/s42949-023-00103-2>

INTRODUCTION

Managing the co-benefits of nature-based solutions (NBS) across climate, biodiversity and society is of critical importance for meeting climate neutrality targets set in the Paris Agreement¹ and biodiversity restoration targets outlined in the Kunming-Montreal Global Biodiversity Framework². Recent studies call for research into the interplay between biodiversity, climate adaptation and mitigation as well as environmental justice outcomes in order to keep global warming within the desired 1.5 degrees Celsius global mean temperature increase, halt global biodiversity loss, and promote human well-being^{3,4}.

However, often biophysical assessments of biodiversity and climate adaptation and mitigation priorities are considered in isolation of social science assessments. Biophysical models demonstrate growing evidence that urban trees^{5–7} and vegetation more widely⁸ including the soil beneath, can also make a significant contribution to mitigating greenhouse gas (GHG) emissions. Models for assessing carbon dioxide (CO₂) flux and the carbon sequestration potential of urban NBS are now becoming well-established^{9,10}. CO₂ flux is the exchange of CO₂ molecules between the atmosphere and underlying surface per surface area and time. Negative values denote that the surface acts as a sink for CO₂ and positive values that it acts as a source.

Similarly, biophysical models demonstrate the biodiversity values of urban NBS, including urban forests and other types of urban green spaces^{11–14}. One way of assessing biodiversity values is through scoring approaches which are simple to use and enable ranking of sites when the consideration of multiple criteria is important^{13,15}, as is common in conservation planning^{16,17}. Scoring approaches can be combined with expert elicitation to

estimate the potential value for biodiversity¹⁸, integrating aspects of species richness, biomass, population density, evenness, and rarity at the whole city scale (following the approach of¹⁹). Models for assessing the trade-offs between biodiversity and carbon mitigation goals have also been developed, principally drawing on biophysical attributes^{20,21}. Collectively, we consider modelled priorities for CO₂ flux and biodiversity informed by scientific knowledge as 'biophysical values.'

We are concerned that climate mitigation, adaptation and biodiversity assessments drawing on biophysical assessments alone will be challenging to implement unless they draw upon social factors²². One important social factor is social acceptability, which describes the extent to which a group of people prefer a given situation²³. Considering social acceptability judgements alongside biophysical attributes can inform the feasibility^{24,25}, uptake and success of management interventions^{26,27}. It also can achieve greater geographic and socio-demographic representation²⁸ necessary for procedural justice outcomes^{29,30}.

Public participation geographic information systems (PPGIS) provides one way of eliciting social acceptability, operationalised in terms of landscape, place or social values³¹. Online PPGIS surveys generally involve random and/or convenience samples of residents or visitors identifying places of importance on a map of a given region using electronic points. In the analysis phase, values of each survey respondent are aggregated together to represent society, hence forming 'social values' or SV³². PPGIS and spatial conservation prioritization approaches have been combined to spatially identify synergies and trade-offs between SV and biophysical values for biodiversity, whereby SV for biodiversity are generated using PPGIS and biophysical values are generated using either scoring or complementary methods for assessing

¹Helsinki Institute of Sustainability Science, University of Helsinki, Yliopistonkatu 3, 00014 Helsinki, Finland. ²Ecosystems and Environment Research Program, Faculty of Biological and Environmental Sciences, University of Helsinki, PO Box 65, 00014 Helsinki, Finland. ³Department of Economics and Management, Faculty of Agriculture and Forestry, University of Helsinki, Helsinki, Finland. ⁴Urban Transformations Hub, Monash University Indonesia, Tangerang Seletan, Banten 15345, Indonesia. ⁵Institute for Atmospheric and Earth System Research/Physics, Faculty of Science, University of Helsinki, PO Box 64, 00014 Helsinki, Finland. ⁶Conservation Biology Informatics Group, Finnish Museum of Natural History, University of Helsinki, Pohjoinen Rautatiekatu 13, Helsinki, Finland. ⁷Department of Geosciences and Natural Resource Management, University of Copenhagen, Rolighedsvej 23, 1958, Frederiksberg, Denmark. ⁸Department of Built Environment, Aalto University, Otakaari 4, 02150 Espoo, Finland. ⁹Climate System Research, Finnish Meteorological Institute, PO Box 503, FI-00101 Helsinki, Finland. ✉email: christopher.raymond@helsinki.fi

conservation priorities^{15,28,33–35}. Socially acceptable and scientifically defensible priorities for conservation can be derived from the spatial overlays of high-high, and high-low value areas of social and biophysical value^{28,34}, enabling the identification of specific geographic locations where conservation options are supported or opposed²⁸.

Even though studies on CO₂ sequestration and possibilities to increase sinks in various habitats have accumulated, the spatial relationships, as well as synergies and trade-offs, between social and biophysical values for biodiversity and CO₂ flux have not been examined to date. Such integrated valuation can inform how to educate and involve residents in the protection of NBS for different outcomes, including managing them jointly for carbon sequestration and storage, biodiversity, and broader sustainability outcomes³⁶. From a policy perspective, the results could be used to harmonise carbon neutrality and biodiversity conservation policies and actions in cities globally. For example, in Europe there is an urgent need to harmonise ambitions under the proposed EU Nature Restoration Law requiring no-net loss of biodiversity by 2030 and 5% gain in urban areas by 2050³⁷ with 2030 or 2035 (depending upon member state) carbon neutrality ambitions.

This paper aims to examine the spatial relationships between biophysical and SV for biodiversity and carbon sequestration potential (measured as CO₂ flux) in the City of Helsinki, Finland. The approach combines methods from carbon sequestration modelling, expert scoring approaches to biodiversity assessment and PPGIS. We consider NBS with respect to the level of intervention³⁸. While most NBS studies tend to focus on type 3 solutions of design and management of new ecosystems³⁹, we focus on type 1 NBS: improving the protection of natural ecosystems like mature forests and protected wetlands/estuaries.

The aim will be addressed through three objectives: 1) to examine the spatial distribution of biophysical and SV for carbon mitigation and biodiversity conservation across different NBS in Helsinki; 2) to spatially examine the overlaps between biophysical and SV for carbon mitigation and biodiversity conservation, and; 3) to identify co-beneficial outcomes and trade-offs associated with the consideration of values for carbon mitigation and biodiversity conservation grounded in different knowledge systems. SV are linked to local knowledge systems and biophysical values are linked to scientific knowledge systems.

Helsinki, the capital of Finland, has a population of 660,000 within the municipal borders (the study area), and a population of 1.5 million in the metropolitan area⁴⁰. According to the European Environmental Agency, the Helsinki metropolitan area is one of the greenest capital regions in Europe with NBS adding up to 62% of the total city area and urban trees cover 44% of the city area⁴¹ (Fig. 1a). The green structure is characterised by seven green wedges (or 'fingers') stretching from the hinterland to the city centre (Fig. 1b). The green wedges are foremost covered by urban forest and in the central part more open green spaces (parks), but also wetlands/estuaries, arable land and pastures.

The City of Helsinki works actively with NBS to promote climate neutrality and biodiversity conservation. NBS are highlighted in the city's biodiversity action plan⁴², and the city is aiming to become carbon-neutral by 2030, mainly by reducing GHG emissions, but also by investigating the carbon sink potentials of urban nature⁴³. However, the backbone of the green structure, the green wedges, are under pressure from urbanisation processes, such as densification⁴⁴. And unlike many other cities, the city of Helsinki has in its master plan allocated some of its green spaces for development, due to the fact that the city is both the main town planning authority and the principal landowner⁴⁵. The new Helsinki Forest Management Strategy is grappling with the conflicting pressures of conservation and development by, for example, increasing planned diversity in forested areas, allowing forests to age naturally and involving the local community in new management actions to adapt to climate change and the impact

of a growing city⁴⁶. This includes new ways of integrating community understandings of biodiversity and carbon sequestration and storage into NBS management options.

RESULTS

Sample representativeness

Survey respondents are more likely to be female, more employed and slightly more educated than what would be expected based on the regional population in Helsinki. The proportion of respondents in young and old age classes are lower than the regional population. Fagerholm et al.⁴⁷ report similar over-representation of females and deviations across background age and employment groups in their PPGIS meta-analysis of five different cities in Scandinavia. The sampling approach ensured spatial representation from all 34 districts in Helsinki (see Supplementary Figure 1). However, we had an under-sampling in the three most populated districts of Kampinmalmi, Mellunkylä and Vuosaari.

Social values by domicile and socio-demographics

Residents mapped SV for biodiversity (3776.9 m) significantly closer to their domicile than SV for carbon sequestration and storage (4451.4 m, $p < 0.001$). Males mapped SV for biodiversity significantly further from their domicile (2702.0 m) compared with females (2393.0 m, $p < 0.001$). Younger respondents (<39 years) mapped SV further from their domicile than older respondents (>60 years), both for carbon and biodiversity ($p < 0.001$). Spatial discounting of values from domicile was less prominent for green wedges on the far eastern side of the city, relative to more central, or western green wedges for both SV for carbon (Kruskal-Wallis $H = 330.4$, $df = 6$, $p < 0.001$), and SV for biodiversity (Kruskal-Wallis $H = 278.5$, $df = 6$, $p < 0.001$). Median differences in value-domicile distances were found by age and education within some green wedges; however, the direction of these differences varied across green wedges.

We found proportional differences in SV by age, gender and income across green wedges ($\chi^2 > 21.0$, $p < 0.05$), but the direction of differences often change across them (Table 1). For example, younger residents assigned proportionately more SV for carbon to Central Park compared with senior residents (30.4 vs. 17.1%), but proportionately fewer SV for carbon (19.7 vs. 33.8%) and biodiversity (22.0 vs. 31.8%) to Western Park. While females assigned proportionately more SV than males to East Helsinki, Viikki-Kivikko and Western parks, this was not consistent for value types nor all wedges. Proportionately more values in the East-Helsinki culture park and Viikki-Kivikko green wedges were mapped by respondents with below- median salary, but the opposite was found in Östersundom and Central park green wedges. Senior respondents assigned proportionately more SV outside wedges compared with younger respondents.

Spatial distribution of CO₂ flux and biodiversity values

We spatially assessed the top 20% of CO₂ flux and biodiversity values, drawing on both biophysical and SV (Fig. 2, Table 2). Areas of overlap between all four value types include diverse urban habitat types. These include mature forests, protected wetlands/estuaries and recreational park areas, but also historically valuable military islands. Most of these enjoy some level of conservation or protection, indicating they are acknowledged in urban planning. The large island just south of Eastern Helsinki wedge is a military island and land cover data from there is limited, bringing large uncertainties in simulating biogenic CO₂ fluxes.

NBS acting as a CO₂ source are concentrated on waste and unused land areas and agricultural fields (Fig. 2a). However, the majority of the study area is acting as a net biogenic sink (i.e.

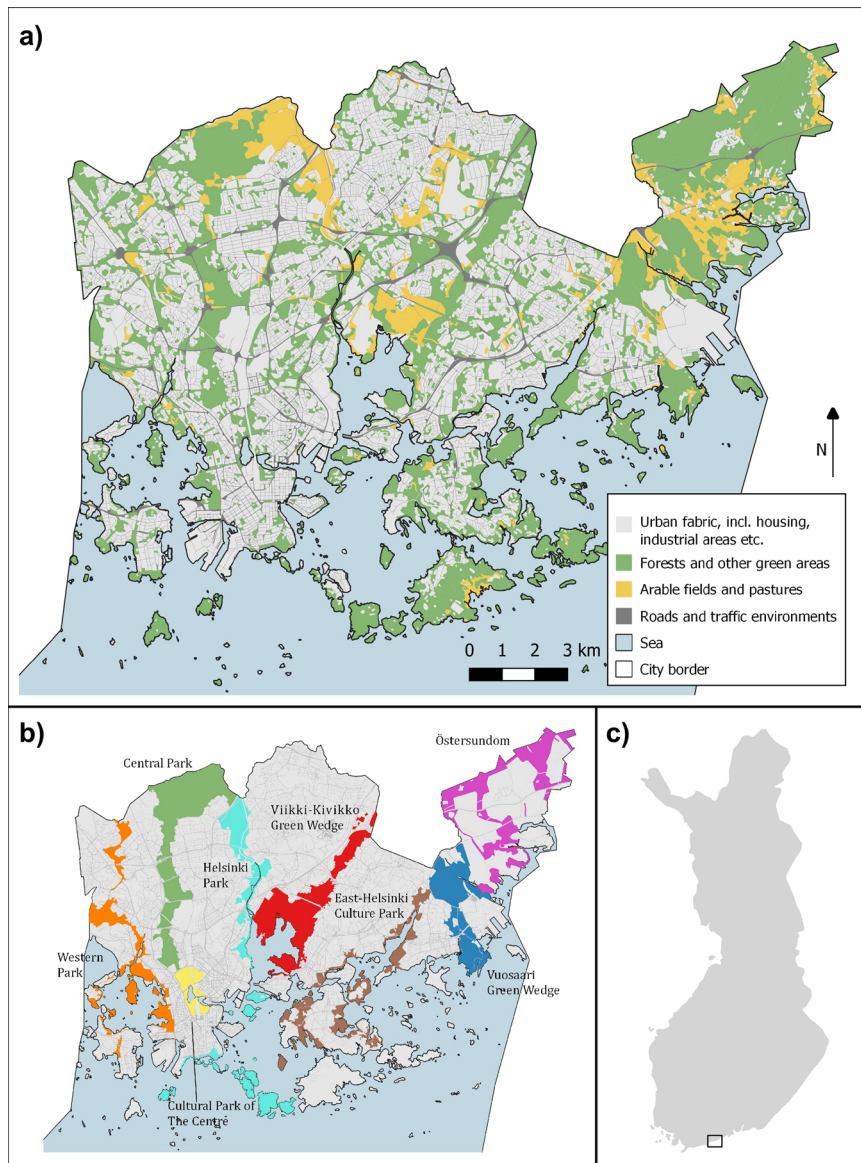


Fig. 1 Map of the city of Helsinki. **a** A simplified depiction of broad urban land use and land cover types and **b** with the green wedges important to the analyses highlighted based on the Urban Atlas 2018⁶⁸. Study area location with respect to Finland is shown in **c**.

negative values). As expected, largest sinks were found in areas with high leaf mass for photosynthesis and sufficient water availability such as urban forests and large park areas. Also constructed green areas and street vegetation acted as a sink but were smaller due to their smaller leaf area. Areas of highest biodiversity values were found in the more remote green wedges, particularly Östersundom (75%) and Vuosaari Green Wedge (50%, Table 2). Nevertheless, areas of moderate biodiversity value were also found close to the urban core. The SV layers coincide with the green wedges, particularly those closer to more densely populated areas. Östersundom and the coastal islands were overlooked. These places may represent either very exclusive areas (western park due to expense, coastal areas due to lack of access) or areas of low population and associated access difficulties (Östersundom).

Top 20% of biophysical and SV for biodiversity and carbon

Biophysical values assessments (CO₂ flux and biodiversity) spatially co-occur and the SV values (carbon and biodiversity) spatially co-occur. The biophysical values are more widespread. There is a

notable difference between the SV and biophysical maps. High values of SV are concentrated in the wedges closer to the urban core while high CO₂ flux and biodiversity values are concentrated in the wedges further from the urban core (Fig. 3). Greatest overlap between all 4 value types can be found in more heavily forested green wedges closer to the urban core or to existing residential areas. Not all overlapping areas are within the existing green wedges of Helsinki and therefore may be at greater risk of development. The correlation matrix of all variables and Spearman's rank correlation coefficients show that all variables are significantly and positively correlated, pointing to a synergistic relationship between all values. SV for biodiversity and carbon were highly correlated ($r = 0.59$, $p < 0.001$), while SV and biophysical values were moderately to weakly correlated ($r < 0.31$, $p < 0.001$) (Supplementary Fig. 3).

Overall, we found similar proportions of biophysical values for CO₂ flux and biodiversity in each Green Wedge, with a few key exceptions. In total, 50% of Central Park was covered with the top 20% of CO₂ values, while only 17% of the area was covered with the top 20% biodiversity values (Table 2). Similarly, 21% of

Table 1. Sociodemographic comparison between mapped social values for biodiversity (SV_BD) and carbon sequestration and storage (SV_Ca) across Helsinki's green wedges.

	Outside Green Wedges				Central park				East-Helsinki culture park				Helsinki park				Viikki-Kivikko				Vuosaari				Western park				Östersundom			
	SV_BD		SV_Ca		SV_BD		SV_Ca		SV_BD		SV_Ca		SV_BD		SV_Ca		SV_BD		SV_Ca		SV_BD		SV_Ca		SV_BD		SV_Ca		SV_BD		SV_Ca	
	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%		
AGE																																
<39	236	20.3	191	20.6	202	30	369	30.4	63	26.9	71	26.9	93	35.9	49	29.7	210	38.3	164	32.8	57	28.1	50	26.2	58	22.0	31	19.7	4	18.2	13	31.7
Stand. resid.	-6.7		-5.3		1.6		3.2		-0.2		-0.1		3.2		0.8		6.2		3.1		0.2		-0.3		-2.1		-2.1		-1		0.7	
40 - 49	335	28.9	216	23.3	217	32.2	333	27.5	59	25.2	36	13.6	66	25.5	32	19.4	136	24.8	131	26.2	54	26.6	48	25.1	65	24.6	33	21	8	36.4	8	19.5
Stand. resid.	0.9		-0.8		2.8		3.3		-1		-4.2		-0.9		-1.5		-1.8		1.1		0.3		0.3		-1.3		-0.9		0.9		-0.7	
50 - 59	280	24.1	265	28.5	136	20.2	303	25	57	24.4	83	31.4	55	21.2	47	28.5	100	18.2	125	25	46	22.7	55	28.8	57	21.6	40	25.5	10	45.5	14	34.1
Stand. resid.	2.1		1.3		-1.3		-1.9		0.9		1.7		-0.3		0.5		-2.3		-1.1		0.2		0.6		-0.2		-0.4		2.7		1	
>60	309	26.6	257	27.7	119	17.7	208	17.1	55	23.5	74	28	45	17.4	37	22.4	102	18.6	80	16	46	22.7	38	19.9	84	31.8	53	33.8	0	0	6	14.6
Stand. resid.	4.1		5.1		-3.4		-4.8		0.3		2.6		-2.1		0.2		-2.4		-3.4		0		-0.6		3.7		3.7		-2.5		-1.1	
GENDER																																
Male	340	26.9	221	22.9	164	22.5	272	20.7	49	18.5	46	15.6	63	22.7	31	17.5	166	27	144	25.4	67	32.2	52	25.1	67	21.9	25	13.9	8	44.4	13	31
Stand. resid.	1.8		1.3		-1.8		-0.8		-2.6		-2.6		-0.9		-1.3		1.2		2.5		2.4		1.3		-1.3		-2.5		1.9		1.5	
Female	926	73.1	743	77.1	565	77.5	1042	79.3	216	81.5	249	84.4	214	77.3	146	82.5	449	73	422	74.6	141	67.8	155	74.9	239	78.1	155	86.1	10	55.6	29	69
Stand. resid.	-1.8		-1.3		1.8		0.8		2.6		2.6		0.9		1.3		-1.2		-2.5		-2.4		-1.3		1.3		2.5		-1.9		-1.5	
EMPLOYMENT																																
Unemployed	236	22.1	202	23.1	140	22.8	282	24.2	73	33.2	76	30	57	23.9	35	22	123	23.2	121	22.9	30	17.6	33	18.8	74	28.7	45	28.7	2	9.5	11	25.6
Stand. resid.	-1.4		-0.7		0.2		0.2		3.5		2.3		0.1		-0.6		-0.2		-0.6		-1.9		-1.9		2		1.4		-1.5		0.2	
Employed	830	77.9	673	76.9	475	77.2	882	75.8	147	66.8	177	70	181	76.1	124	78	407	76.8	407	77.1	140	82.4	143	81.3	184	71.3	112	71.3	19	90.5	32	74.4
Stand. resid.	1.4		0.7		0.5		-0.2		-3.5		-2.3		-0.1		0.6		0.2		0.6		1.9		1.7		-2		-1.4		1.5		-0.2	
EDUCATION																																
Undergraduate	141	12.8	140	15.6	80	12.6	174	14.5	36	16.1	51	20	35	14.4	25	15.5	60	11.1	88	16.4	18	10.4	29	16.2	37	13.9	31	19.5	6	27.3	11	24.4
Stand. resid.	-0.1		-0.4		-0.2		-1.7		1.5		1.8		0.7		-0.2		-1.4		0.3		-1		0.1		0.5		1.2		2		1.6	
Graduate	957	87.2	759	84.4	554	87.4	1025	85.5	187	83.9	204	80	208	85.6	136	84.5	479	88.9	449	83.6	155	89.6	150	83.8	229	86.1	128	80.5	16	72.7	34	75.6
Stand. resid.	0.1		0.4		0.2		1.7		-1.5		-1.8		-0.7		0.2		1.4		-0.3		1		-0.1		-0.5		-1.2		-2		-1.6	
INCOME																																
Below median	548	50.7	445	49.3	309	49.1	623	52.6	145	62.8	167	61.6	138	57.5	91	57.2	299	55.2	330	61.9	90	52	90	47.9	136	52.3	81	51.3	7	31.8	18	39.1
Stand. resid.	-1.6		-3		-2		-0.8		3.2		2.8		1.6		0.9		1.3		4.2		-0.2		-1.6		-0.1		-0.6		-2		-2	
Above median	533	49.3	458	50.7	320	50.9	561	47.4	86	37.2	104	38.4	102	42.5	68	42.8	243	44.8	203	38.1	83	48	98	52.1	124	47.7	77	48.7	15	68.2	28	60.9
Stand. resid.	1.6		3		2		0.8		-3.2		-2.8		-1.6		-0.9		-1.3		-4.2		0.2		1.6		0.1		0.6		2		2	

The table shows proportional differences in mapped social values for biodiversity and carbon by socio-demographic type within a given green wedge. Proportional differences need to be read down the page and within a column. Darker shades represent proportionately more points assigned while lighter shades represent proportionately fewer points assigned with a given socio-demographic category (e.g., age). Shaded cells represent adjusted standardized residuals of statistically significant associations between sociodemographic variables and green wedge type.

Western Park was covered by the top 20% CO₂ flux values, while only 4% of the park was covered by biodiversity values. In general, Western Park had the greatest area of no identified values (70%, Table 2). Differences in the spatial distribution of biophysical and SV were identified across the region (Table 2). Green wedges closer to the urban core had the greatest cover of both biophysical and SV, evidenced by Central Park (CO₂ flux = 50%, SV Carbon = 22%; Biodiversity = 17%, SV Biodiversity = 20%) and Viikki and Kivikko (CO₂ flux = 40%, SV Carbon = 18%; Biodiversity = 34%, SV Biodiversity = 27%). However, green wedges further from the urban core generally had higher cover of biophysical values for both biodiversity and carbon, and lower SV for each type. In other words, SV were concentrated in the central more urban green wedges and the biophysical values were more dispersed.

Management scenarios for nature-based solutions

We assessed the spatial distribution in priorities for different NBS management scenarios in Helsinki (Fig. 4). *Scenario 1 — biophysical values maximiser* (Fig. 4a) involves managing NBS for the top 20% of biophysically assessed carbon flux and biodiversity values. These areas are of the highest biodiversity value and have the highest carbon sequestration potential. The highest proportion of the study area (9%) is managed under this scenario. Management of forests for both biodiversity and carbon outcomes in this scenario would occur mainly in the northeast sections of the region, including the Östersundom (58% of wedge) and

Vuosaari (34%) green wedges. Areas of Helsinki Park (23%) and Central Park (15%) are also important for both carbon and biodiversity. *Scenario 2 — SV maximiser* (Fig. 4b) involves managing NBS for the top 20% of SV for carbon and biodiversity. Management under this scenario is restricted to principally to Viikki-Kivikko park (17%) and Central Park (16%). In total 2.70% of the study area is managed. *Scenario 3 — Carbon maximiser* (Fig. 4c) involves managing areas that contain the top 20% of biophysical values for CO₂ flux and SV for carbon. Priority areas for management in this scenario are similar to those for Scenario 2, with highest scores Viikki-Kivikko park (13%) and Central Park (21%). In total, 2.78% of the study area is managed. *Scenario 4 — Biodiversity maximiser* (Fig. 4d) involves managing areas that contain the top 20% of biophysical values for biodiversity and SV for biodiversity. Fewer sites for management in Viikki-Kivikko (10%) and Central Park (7%) were found in this scenario compared with Scenarios 2 and 3. In total, 2.41% of the study area is managed. *Scenario 5 — All top 20%* (Fig. 4e) involves managing areas for the top 20% of values for all layers. The least amount of NBS is managed under this scenario (1.31% of the total study area).

DISCUSSION

In this study, we presented a new integrated valuation method for spatially comparing priorities for NBS management for carbon mitigation and biodiversity conservation, drawing on biophysically assessed and social value perspectives. We highlight the critical

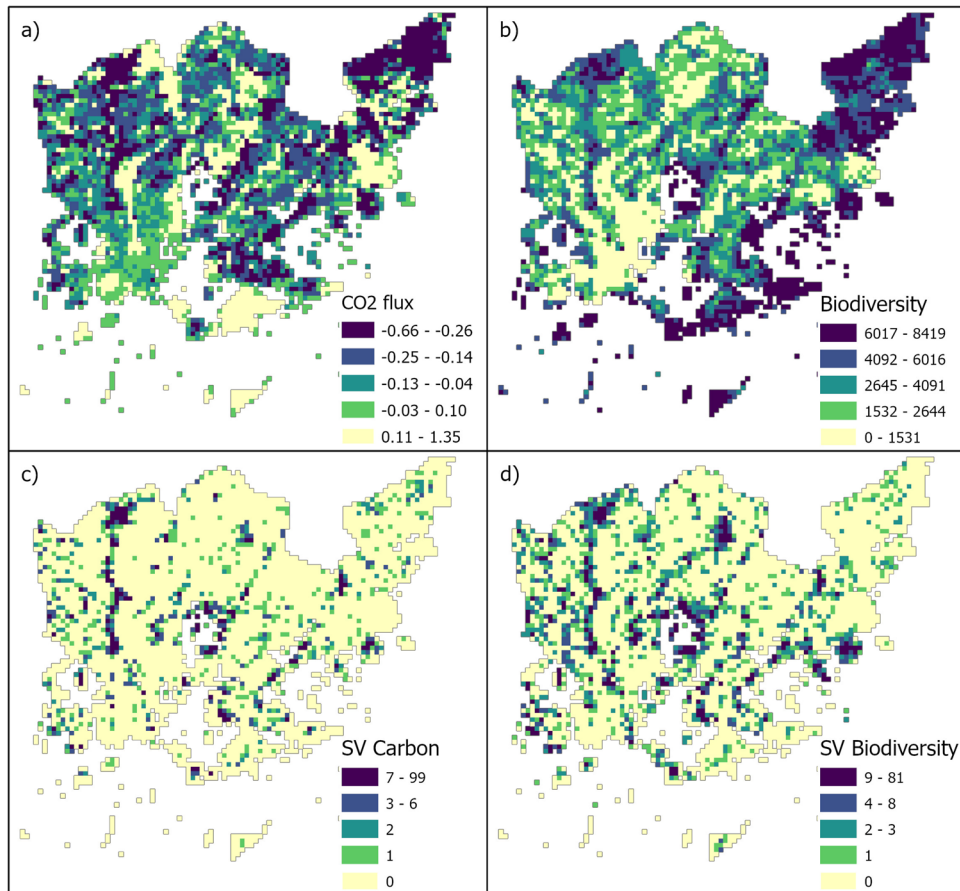


Fig. 2 Spatial distribution of biophysical and social values for carbon and biodiversity. Base layers for **a** CO₂ flux (kg C m⁻² year⁻¹) where negative values indicate a carbon sink and positive values are sources, **b** Biodiversity, **c** SV for Carbon represented by the number of records, **d** SV for Biodiversity. Graduate colour schemes scaled by quantiles. Bivariate comparison between each layer can be found in Supplementary Fig. 2.

importance of protecting existing NBS for biodiversity and carbon mitigation outcomes based on biophysical assessments, while also taking account of SV to increase the social acceptability of NBS management and implementation efforts.

We demonstrated how ecological, carbon flux and social acceptability criteria can be applied to identify opportunities for biodiversity conservation and carbon mitigation. The strong alignment between biodiversity and carbon sink areas points to the importance of protecting existing vegetated, especially forested, landscapes for biodiversity and carbon mitigation outcomes. The City of Helsinki has a biologically rich landscape comprising of mainly forests, but also wetlands and open rocks, and semi-natural areas including meadows and pastures⁴⁸. Much of the academic scholarship at present is on the tensions between biodiversity and carbon mitigation outcomes in the design and implementation of NBS^{49,50}; however, these findings remind us that protecting and restoring existing NBS in urban areas is vital for achieving both carbon mitigation and biodiversity goals.

Building on earlier work^{15,28,34}, the results highlight that residents can provide important and valid spatial information for biodiversity conservation particularly in areas closer to the city core which are more accessible to a higher number of residents. We extend previous research by showing that there is potential for synergies between biodiversity and SV in protected areas and nature sites³⁵. However, integration of SV for biodiversity and carbon can also lead to sub-optimal conservation and carbon mitigation outcomes, as demonstrated by the large spatial disconnects in biophysical and SV in green wedges located further away from the urban core. Such disconnects highlight

the need for some caution in the application of social data to conservation and carbon mitigation assessments⁵¹, for example, balancing human access to healthy habitats and the creation of opportunities for non-human species to flourish⁵². Biodiversity and carbon sequestration concepts are challenging concepts to understand, and we did not expect that biophysical and social values would spatially align in all places. We contend that the results provide pathways for raising awareness and building capacity for joint biodiversity conservation and carbon mitigation actions, while also spotlighting areas that are both scientifically defensible and socially acceptable for climate mitigation, adaptation and biodiversity conservation.

It remains unclear as to whether residents are assigning values for biodiversity and carbon based on accessibility criteria (akin to experiential knowledge) or based on deeper cognitive understanding of biodiversity and carbon mitigation concepts. The strong spatial correlation between SV for biodiversity and carbon sequestration suggests that respondents assigned these values to similar areas. The fact that males and younger respondents are assigning their values further from domicile than female and older respondents suggest that accessibility and experience indicators are influencing value attribution to both carbon mitigation and biodiversity conservation. The variation in SVs by green wedge type and socio-demographics support earlier assessments showing that SV (in that case perceived biodiversity and recreation) in Helsinki were significantly affected by geographic area, gender and income⁵³.

Value assignment could also be influenced by the convenience sampling approach. Most value dots were assigned to districts

Table 2. Percentage of each park area covered by top 20% pixels within Helsinki's green wedges.

	Helsinki park	East-Helsinki culture park	Central park	Western park	Östersundom	Viikki-Kivikko Green Wedge
Vuosaari						
Green Wedge	7.30	5.45	12.27	5.40	7.41	6.30
Park total area (km ²)	10%	43%	50%	21%	60%	45%
Top 20% Carbon	22%	35%	17%	4%	75%	50%
Top 20% Biodiversity	7%	11%	22%	7%	0%	10%
Top 20% Soc Val Carbon	14%	19%	20%	17%	0%	15%
Top 20% Soc Val Biodiversity						
Top 20% over-lap	66%	46%	70%	23%	43%	66%
	23%	23%	17%	19%	20%	23%
	5%	13%	6%	58%	20%	5%
	3%	11%	7%	0%	6%	3%
	3%	7%	0%	0%	10%	3%

Percentages are calculated separately for each park, based on the park's total area. The top 20% overlap values represent the percentage of pixels with 0 to 4 top 20% pixels overlapping for carbon, biodiversity, SV for carbon or SV for biodiversity adding up to 100%. For example, a top 20% overlap value of 4 refers to pixels where a top 20% valued pixel from each category is found in the same pixel.

within the urban core that are also highly populated (Supporting Fig. 1). An under-sampling occurred in three highly populated districts of Kampinmalmi, Mellunkylä, Vuosaari, resulting in proportionately fewer mapped points in those areas.

Yet green wedge type and socio-demographics cannot consistently explain differences in the spatial distribution of SV. Irrespective of the basis for value, the results demonstrate that NBS protection measures, for carbon mitigation, biodiversity conservation or both, should be combined with public acceptance of measures of carbon sequestration and storage, including the types of plantings and the nature of dead matter to be retained in a given green space. In locations where SV for carbon or biodiversity align with biophysical values, the social acceptability measures can be used to prioritise carbon mitigation, adaptation and biodiversity conservation efforts. Equally, areas of low carbon and low biodiversity priorities based on biophysical assessment and SV assessments could be discounted in the planning process.

Our integrated assessment also provides vital information about how to design capacity building and awareness raising opportunities, particular in areas of spatial disconnect between SV and biophysical priorities (Table 3). For example, areas of high carbon and high biodiversity but low social values for both attributes could be focal areas for education about why carbon sequestration is important in these areas, and what species or ecosystems contribute to the biodiversity values found there.

Caveats

The green wedges as planning tools capture the “most important areas”, but there are large areas of moderate biodiversity value not covered by them. One needs to also take these outlying areas into planning and into future regional assessments of the spatial overlaps between biophysical and SV of biodiversity and carbon sequestration potential. The research focuses on the management of existing NBS for carbon sequestration and biodiversity conservation, but does not directly inform biodiversity restoration efforts. Also, the research focuses on priority areas for management. The type of management that would best foster both biophysical and SV may depend on what kind of ecosystems these areas include in addition to community preferences for engagement and just outcomes.

Integrated valuation necessarily involves combining values that have different metrics. Indeed, there are operational differences in how we assessed ‘value’ across biophysical and SV perspectives. For example, in the carbon models we assessed carbon flux in terms of whether a given site is a source or sink for carbon on annual basis, without considering emissions related to planting or maintenance of urban trees as their full lifecycle was not assessed, while in the SV for carbon we asked individuals to identify areas that are highly important for carbon sequestration AND storage. Future research could refine the operational measures across knowledge systems to aid more direct comparisons also including the emissions arising from the seedling production, transport and maintenance of urban trees and their growing media.

The bias towards female and employed respondents is an important limitation of this study, but confirms previous work showing that issues of gender⁵³ and socio-economic vulnerability⁵⁴ influences the assignment of SV. Women also respond more often to studies on green areas in the Nordic region⁴⁷. While socio-demographic factors can influence the number of points assigned to a map, socio-demographic biases wrought by different sampling techniques (e.g., convenience vs. representative), have been found to have little influence on location accuracy of SV⁵⁵. It was difficult to test this hypothesis in the current paper given that most data were collated through a convenience sample. Future research could engage more diverse, including marginalised groups, in the assessment of social acceptability to better understand ‘whose values’ rather than what values and

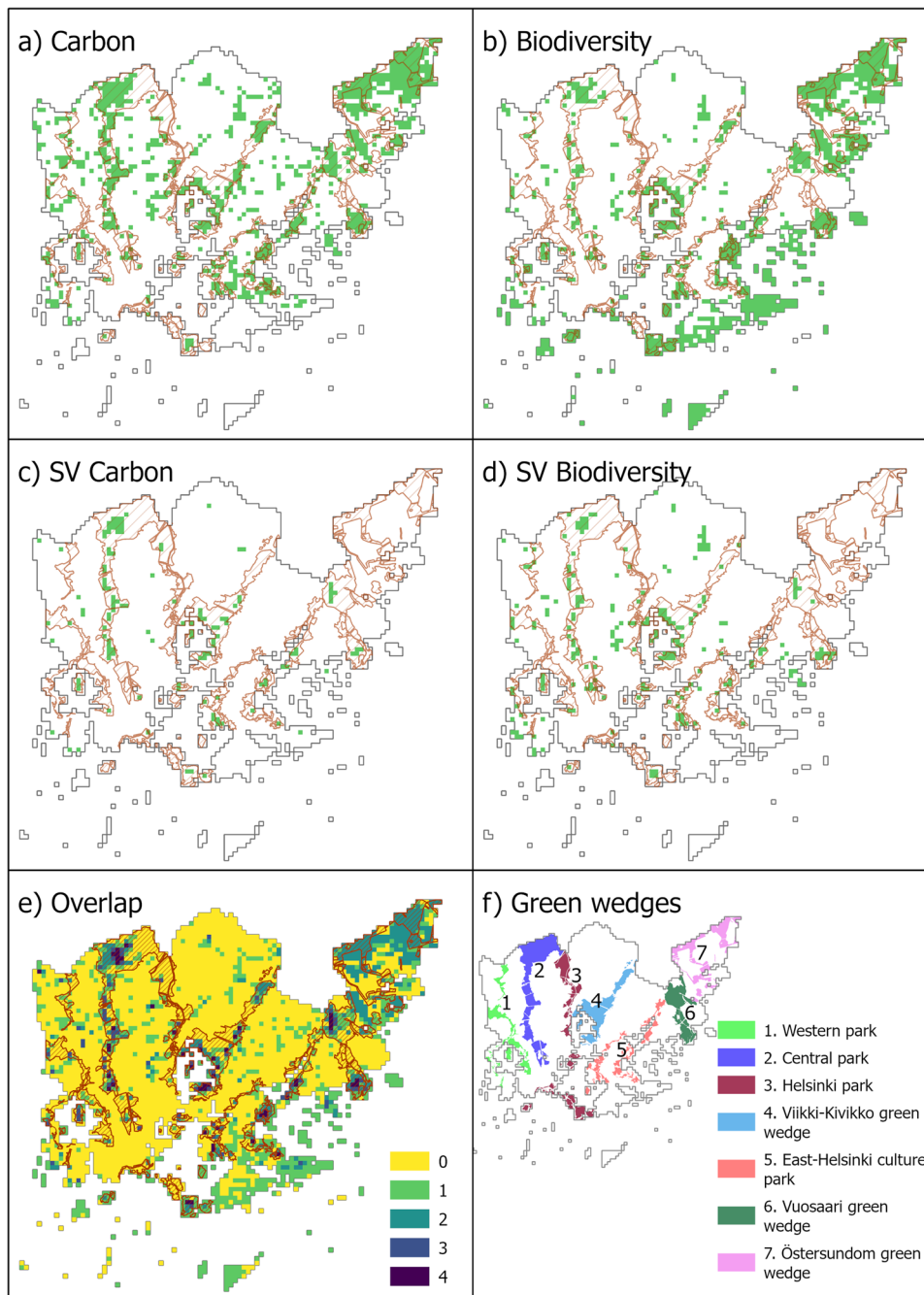


Fig. 3 Spatial overlap of biophysical and social values for carbon and biodiversity. Top 20% locations for **a** CO₂ flux, **b** Biodiversity, **c** SV for Carbon, **d** SV for Biodiversity and **e** number of overlapping indicators from **a–d**. Graduated colour schemes scaled by quantiles. **e** Sum of all top 20% locations. **f** location of green wedges.

where are likely to be affected by different biodiversity conservation and climate mitigation and adaptation strategies. This approach reflects current calls for just processes in urban green transitions for climate neutrality and biodiversity enhancement⁵⁶.

METHODS

Socio-demographic and spatial discounting analyses

Chi-square analysis (test for independence) with standardized residuals was conducted to identify proportional differences between socio-demographic variables (age, gender, employment, education, income) and mapped SV for the whole region and

within Helsinki's green wedges. A residual is the difference in the observed frequency and the expected frequency (i.e., the value that would be expected under the null hypothesis of no association). It is calculated by dividing the residual value by the standard error of the residual. Residuals represent normalized score. If greater than 2.0, they indicate that a significantly greater number of individuals mapped a given social value type than would be expected. We also compared the socio-demographics of all survey respondents compared to municipality census data⁵⁷.

To examine median ranks for mapped distance of domicile to mapped important green places, we conducted Euclidean distance tests in ArcGIS. When then compared median distances

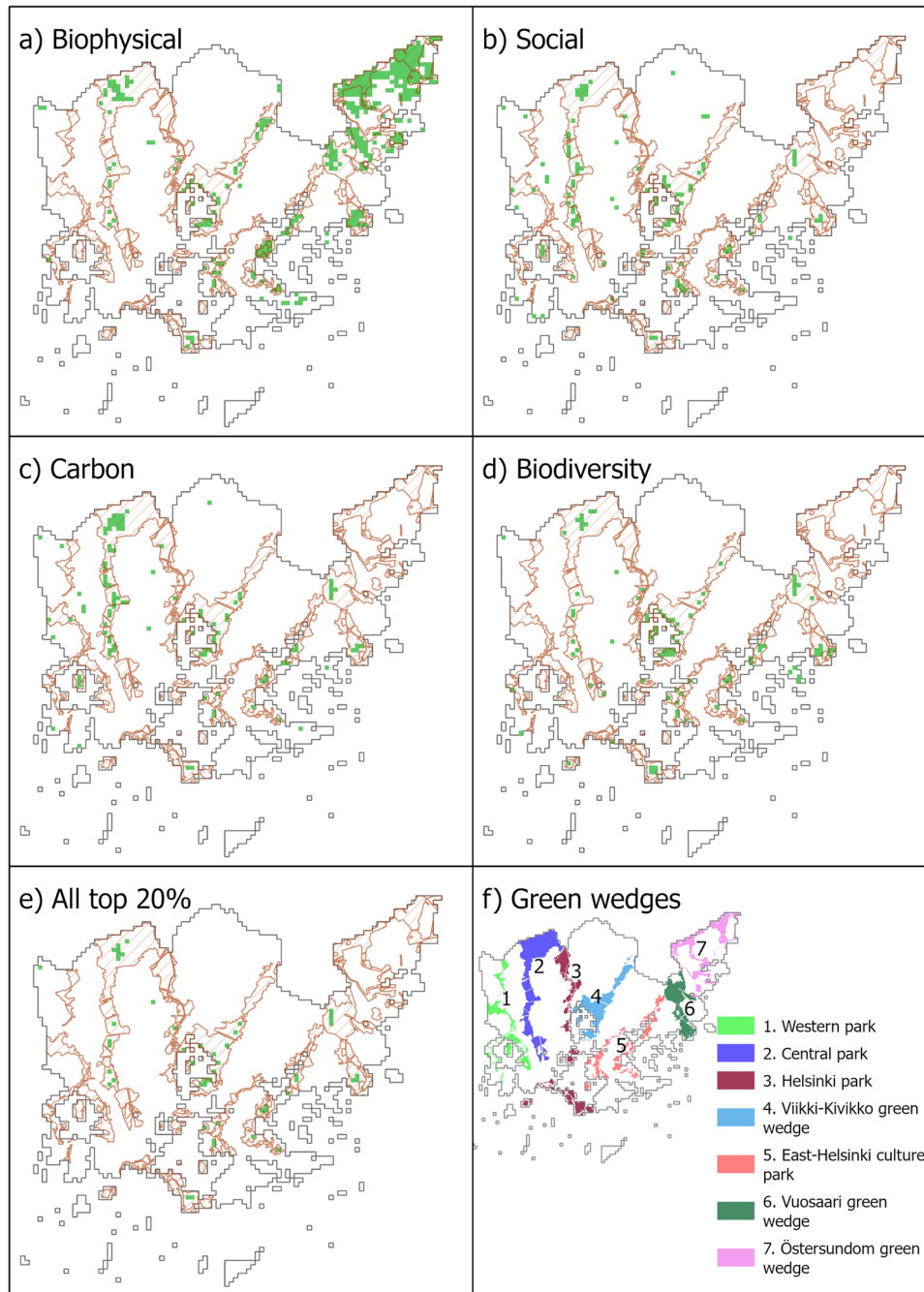


Fig. 4 Management scenarios for nature-based solutions. Four synergies **a** biophysical value maximiser (overlap of top 20% Carbon Flux & Biodiversity), **b** SV maximiser (overlap of top 20% SV Carbon & SV Biodiversity), **c** carbon maximiser (overlap of top 20% Carbon and SV Carbon), **d** biodiversity maximiser (overlap of top 20% biodiversity & SV Biodiversity, **e** carbon and biodiversity biophysical and SV balancer (overlap of top 20% values).

across socio-demographic variables using ANOVA (Kruskal-Wallis test) in relation to (1) SV for biodiversity and (2) SV for carbon.

Modelling of CO₂ flux

The spatial variability of CO₂ fluxes were simulated in Helsinki in 2020 by dividing the land area of the city to 250 × 250 m grids. We used this resolution because it aligns with the urban-rural classification system in Finland, and our results will therefore support wider planning efforts. The model used in the calculations was the Surface Urban Energy and Water balance Scheme SUEWS^{58,59} which has recently been updated to simulate

anthropogenic and biogenic CO₂ surface fluxes¹⁰. For each grid, surface information including fraction of different surface covers (buildings, paved surfaces, base soil, trees/shrubs and turf grasses), tree and building heights, was obtained by combining airborne lidar scanned dataset with city level land use maps⁶⁰. Vegetation in each grid was divided into three classes, urban forest, parks and street trees, based on the Urban tree database of the City of Helsinki. In each grid, the dominant vegetation class was used, defined by the area of urban forests and the number of street or park trees. Each class has their own surface conductance parameterisations based on CO₂ flux observations conducted in different ecosystems. Urban forest parameters were obtained from

Table 3. Options to build capacity and raise awareness about carbon sequestration and storage and biodiversity conservation

	Low carbon, low biodiversity	Low carbon, high biodiversity	High carbon, low biodiversity	High carbon, high biodiversity
Low SV carbon, low SV biodiversity	Discount areas: neither socially acceptable nor of high biological priority to conserve	Scientifically defensible but not socially acceptable for biodiversity conservation. Focal areas for education about biodiversity values.	Scientifically defensible for but not socially acceptable for carbon mitigation. Focal areas for education about carbon values.	Scientifically defensible for carbon mitigation and biodiversity conservation, but low social acceptability for each outcome. Critical areas for education about both the biodiversity and carbon mitigation benefits of NBS.
Low SV carbon, high SV biodiversity	Opportunistic biodiversity conservation efforts may take place; further community engagement recommended to determine why these areas are biologically important to the community but of low carbon value.	Socially acceptable and scientifically defensible areas for biodiversity conservation, but not carbon mitigation actions. Priority areas for biodiversity conservation efforts, irrespective of carbon outcomes.	Mixed views across local and scientific communities. Areas with the highest potential for conflict.	Shared conservation priorities. Further community engagement recommended to determine why these areas are biologically important to the community but of low carbon value.
High SV carbon, low SV biodiversity	Important only to the community for carbon mitigation. Further community engagement recommended to determine why these areas are important for carbon mitigation.	Mixed views across local and scientific communities. Areas with the highest potential for conflict.	Socially acceptable and scientifically defensible for carbon mitigation, but not biodiversity conservation. Invest in carbon neutrality efforts only.	Socially acceptable and scientifically defensible for both carbon mitigation and biodiversity conservation actions but conflicting views on biodiversity outcomes. Priorities for education and awareness raising about biodiversity values.
High SV carbon, high SV biodiversity	Socially acceptable areas for both biodiversity conservation and carbon mitigation, but not scientifically defensible for either value type. Here it is crucial to recognise the plurality in what biodiversity means to different people of diverse worldviews and knowledge systems.	Socially acceptable for both biodiversity conservation and carbon mitigation, but only scientifically defensible for biodiversity conservation. Need to determine why these areas are important to the community for carbon mitigation.	Socially acceptable for both biodiversity conservation and carbon mitigation, but only scientifically defensible for carbon mitigation. Community engagement recommended to determine why these areas are biologically important to the community.	Priority areas for management given their high level of social acceptability and scientific defensibility.

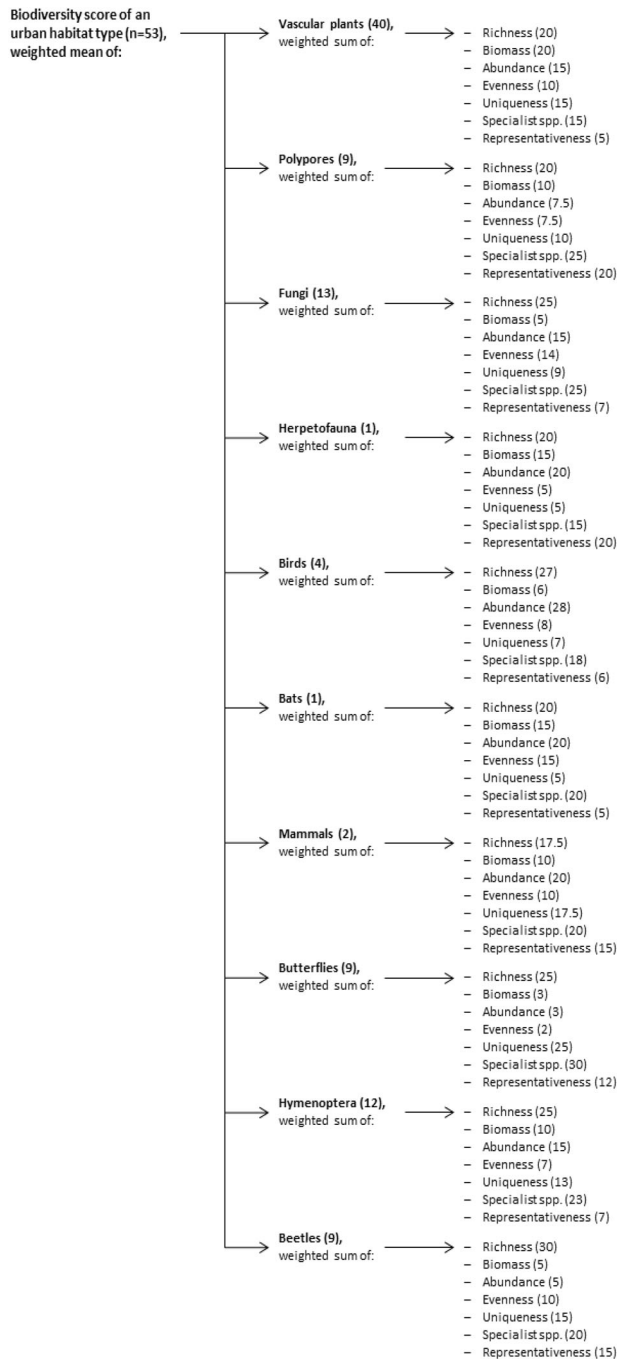


Fig. 5 Scores assigned to components of biodiversity. Scores for different urban habitat types were calculated as weighted mean of scores for different taxa, that themselves were calculated as weighted sums of expert-given scores regarding Biodiversity Quality attributes. Weights are shown in parentheses. Both the inter-taxon weights, and the attribute weights within each taxon score add to 100.

ecosystem level eddy covariance measurements made in broad-leaf forest in Harvard, US⁶¹, street tree parameters from leaf-level gas exchange measurements made from street trees in Helsinki⁶² and park areas gas exchange measurements from gas exchange observations made in a park in Helsinki⁶³.

SUEWS was forced by hourly data for 2020. The meteorological forcing dataset consisted of air temperature, precipitation, short-wave and longwave radiation, relative humidity, air pressure and

wind speed. The main data source was the Kumpula weather observation station (60.20307N; 24.96131E) operated by the Finnish Meteorological Institute. The data was gap-filled by observations from the urban measurement station SMEAR III also located in Kumpula⁶². Any remaining data gaps were filled by hourly ERA5 Land data⁶⁴.

Modelling of biodiversity values

For biodiversity, we used the datasets by Jalkanen et al.¹³ that are distributed openly (see data availability section). In the study, local taxonomic experts scored urban habitat types in terms of their relevance for urban biodiversity in Helsinki. The assessment of biodiversity values was built upon the Biodiversity Quality framework¹⁸, and it comprised of seven metrics that jointly describe the species assemblages in a given location and can be used for scoring different areas in terms of their significance for biodiversity. The metrics include: species richness, total biomass, abundance, evenness (do some individual species dominate the communities, or are individuals evenly distributed across species), uniqueness (are the species assemblages such that are not found in other urban habitat types), habitat specialist species, and regional representativeness (how representative or 'natural' are the urban habitat types compared to similar habitats found in nearby rural areas).

In 2016, 24 local taxonomic experts scored 68 terrestrial urban habitat types in terms of their general support for the Biodiversity Quality attributes of their taxon. Evaluated habitats ranged from seminatural habitats (e.g. old-growth forests, shoreline meadows) to anthropogenic environments (e.g. private gardens, golf courses, managed parks). The elicitation covered ten taxa: vascular plants, polypores, fungi (excluding polypores), herpetofauna (reptiles & amphibians), birds, bats, mammals (excluding bats), butterflies, hymenoptera, and beetles. Elicitation was done by 2–3 experts per taxon. The experts scored each habitat type in terms of how well they support each of the 7 Biodiversity Quality attributes of their taxon (scale of 0–4). In addition, experts assessed the confidence of their answers separately for each Biodiversity Quality attribute. Taxon- and attribute-specific score was calculated as the mean of respective expert answers, weighted by answers' self-assessed confidence. In other words, 'bird richness score for golf courses' was calculated as the average of all bird experts' confidence-weighted scores for golf courses. To emphasise confident answers, the confidence coefficient could be 0, 1, 2, 4, or 8, corresponding to "very unconfident", "unconfident", "somewhat unconfident", "somewhat confident", and "very confident" answers, respectively. See Jalkanen et al.^{13,19} and survey (<https://zenodo.org/record/1255899>) for exact questions and habitat descriptions given for the experts, and the expert answers.

The composite score of a taxon for each habitat type was calculated as the weighted sum of all Biodiversity Quality attributes assessed for the taxon (Fig. 5). The weights were defined by the experts in a workshop, based on the relevance of the attribute for the persistence and functioning generated by the local urban species assemblages. Finally, the total biodiversity score of a habitat type was calculated as the weighted mean of all taxon-specific scores. Taxa had been collaboratively weighted by the experts in a workshop, based on the overall relevance of the taxa for the functioning and persistence of urban ecosystems. For example, plants (40% of weight points) were seen as much more important for urban ecosystems than bats (1%)¹³ (see Supporting Material 3 for weights).

The spatial biodiversity layer was based on an urban habitat map that was compiled for Helsinki from several GIS sources. The map comprised of 53 urban habitat types (no spatial data was available for all small-scale habitat types) and covered all public and private land. The resolution of the raster-type map was 20 × 20 m. Each habitat type class was then reclassified to the

Table 4. Five scenarios represented by the overlap areas between top 20% pixel values for a range of combinations of carbon flux, biodiversity and SV for Carbon and Biodiversity.

	Carbon Flux	Biodiversity	SV Carbon	SV Biodiversity
Scenario 1: biophysical values maximiser	Top 20%	Top 20%		
Scenario 2: social values maximiser			Top 20%	Top 20%
Scenario 3: carbon maximiser	Top 20%		Top 20%	
Scenario 4: biodiversity maximiser		Top 20%		Top 20%
Scenario 5: carbon and biodiversity biophysical and social values balancer	Top 20%	Top 20%	Top 20%	Top 20%

corresponding biodiversity score (i.e., the composite score over all taxa and Biodiversity Quality attributes). Scores ranged from 1283.3 (sealed apartment block yards) to 10772.8 (old-growth groves). Paved surfaces (roads, buildings, etc.) were treated as 0 and waterbodies as missing data¹³.

Modelling of social values for carbon and biodiversity

The SV for biodiversity and carbon data were collected using a public participation geographic information system (PPGIS) online survey distributed among residents of Helsinki from September to November 2021 (Supplementary Methods). The sample was generated using a mixed-mode approach⁶⁵. First, we randomly distributed the survey link to 1000 households in Helsinki through a postal invitation with subsequent follow-up reminders after 15 days. Additionally, the survey was advertised on social media (i.e. Facebook groups from local residents' associations), online newspapers, and other media coverage.

A total of 3237 people responded to the survey, of which 1208 completed most questions. Participants mapped a total of 23,187 point locations in terrestrial locations within the study area representing green spaces with perceived high biodiversity ($n = 3633$), natural values ($n = 3497$) and high carbon ($n = 3787$). Participants could assign as many or as few dots as they wished to the Helsinki region. The responses to the survey were obtained mainly from social media engagement, which represented 80.75% of the sample from which we had distribution information ($n = 857$). Additionally, 5.48% of the responses were obtained by friends and colleagues sharing the survey within their social network. Postal invites led to a survey response rate of only 3.30% (33 responses from the 1000 random invitations). Local associations, newspapers and other distribution channels represented 3.15, 1.63 and 3.85% of the sample, respectively.

More females ($n = 2308$; 71.3%) than males ($n = 725$; 22.4%) participated in the survey, highlighting over-representation of females in survey responses (compared to 52.48% females in the Helsinki region). More than half of our survey respondents (54.2%) were between 35 and 65 years of age, with younger (<35 years) and older respondents (>65 years) being underrepresented compared to the population of Helsinki (16.2% sample vs. 34.8% region <35 years; 12.8% sample vs. 20.1% region >65 years). Additionally, the number of respondents possessing at least upper secondary education was higher (98.9%) relative to the population of Helsinki (76.8%)⁵⁷. Unemployment rates for all the age groups were lower for our respondents compared to the population of Helsinki (ibid), most likely explaining the higher median yearly income of our survey respondents (40,573 €), compared to the residents of Helsinki (38,736 €)⁶⁹. These results indicate a slight bias to middle-aged, more educated and employed respondents with higher incomes in the Helsinki survey compared to regional census statistics from Helsinki.

This paper is based on three mapping questions and on the socio-demographic background of respondents. The spatial questions asked respondents to map: 1) their favourite green spaces in Helsinki and the reasons for their importance (based on a drop-down menu); 2) green spaces perceived as high value for

carbon sequestration and storage in Helsinki, and; 3) green spaces perceived as high value for biodiversity in Helsinki. Respondents had the opportunity to add a short text elaborating on their perceptions in the last two mapping questions.

To derive SV Biodiversity, survey participants were asked to map places they considered biodiversity to be high in the urban green spaces of Helsinki. To derive SV Carbon, the points representing importance places for carbon sequestration or storage were used. Survey participants were asked to map places they considered carbon sequestration and storage to be high in the urban green spaces of Helsinki. Then using a 250 m grid cell the aforementioned mapped PPGIS points within each grid cell were counted. From this, a grid layers representing the number of points for SV Carbon and Biodiversity were generated.

Spatial overlay analyses

We performed spatial overlay analyses to assess the spatial relationships between biophysical and SV for carbon and biodiversity. All datasets were first pre-processed using a common grid of 250 m which represented the coarsest resolution spatial dataset (CO₂ flux) and also a spatial scale relevant to urban planners. Furthermore, the choice of 250 m resolution addresses uncertainty associated with the challenge of accurately mapping small and linear green spaces⁶⁶.

To address the difficulties associated with combining, comparing and analysing data derived through radically different analytical methods (e.g., social data versus modelled biophysical data, measurement scales, maximum and minimum values, and spatial abstraction) each layer was combined based on their ranked values. Using the ranked values was especially important as each dataset had very different, non-normally distributed values, making comparisons using absolute values conceptually difficult. The application of ranked values and identification of high-ranking values as a proxy for priority conservation area is common in spatial conservation prioritisation such as in the application of conservation planning software like Zonation⁶⁷.

Firstly, we mapped quintiles, specifically the top 20% of CO₂ flux, biodiversity values and both biophysical and SV. These top 20% values were used to represent priority areas for the application of NBS in local policy. We chose top 20% based on a sensitivity analysis of top 20 vs. 30% values (Supplementary Table 1). While the total area of the hotspots increased in the top 30% analysis, the broad patterns of high and low values across the parks and within the parks tended to hold. Next, we summed all top 20% values to assess the spatial relation between top 20% values. Finally, we assessed overlapping area using various combinations of top 20% pixels of CO₂ flux, biodiversity and SV for carbon and biodiversity, for five different scenarios: 1. biophysical values maximiser, 2. SV maximiser, 3. carbon maximiser, 4. biodiversity and 5: carbon and biodiversity biophysical and SV balancer (Table 4). We characterised these scenarios for the whole study area and also within the seven green wedges.

The application of a threshold to ranked values based for a number of criteria is commonly used in the spatial conservation

planning literature¹⁹. We chose 20% as it represented reasonable threshold for determining a subset of the study area that represent priority hotspots. However, we also calculated the top 33% values (i.e. the top third of values) to test the sensitivity of the spatial patterns to the choice of threshold value (see Supplementary Fig. 3 for further information).

DATA AVAILABILITY

All non-spatial data generated or analysed during this study are available from the following websites. Biodiversity values were created based on an open dataset by Jalkanen & Vierikko 2022 (<https://doi.org/10.5281/zenodo.6563190>), which includes a map of urban habitat types in Helsinki and the results of an elicitation by local taxonomic experts. See the dataset for the full list of urban habitat types and their descriptions, and exact questions given for the experts. CO₂ flux for Helsinki obtained from SUEWS model run is available as an open dataset by Havu et al., 2022 (<https://doi.org/10.5281/zenodo.7198140>). Data availability subject to controlled access: privacy and ethical issues prevent us from sharing unit record data on SV for carbon and biodiversity. Access requests can be sent to christopher.raymond@helsinki.fi.

Received: 17 October 2022; Accepted: 17 March 2023;

Published online: 18 April 2023

REFERENCES

- UNFCCC. *Adoption of the Paris Agreement, 21st Conference of the Parties*. <https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement> (2016).
- CBD. *Kunming-Montreal Global Biodiversity Framework*. <https://www.cbd.int/conferences/2021-2022/cop-15/documents> (2022).
- Pascual, U. et al. Governing for Transformative Change across the Biodiversity–Climate–Society Nexus. *Bioscience* **72**, 684–704 (2022).
- Seddon, N. Harnessing the potential of nature-based solutions for mitigating and adapting to climate change. *Science* **376**, 1410–1416 (2022).
- Davies, Z. G., Edmondson, J. L., Heinemeyer, A., Leake, J. R. & Gaston, K. J. Mapping an urban ecosystem service: quantifying above-ground carbon storage at a city-wide scale. *J. Appl. Ecol.* **48**, 1125–1134 (2011).
- De la Sota, C., Ruffato-Ferreira, V. J., Ruiz-García, L. & Alvarez, S. Urban green infrastructure as a strategy of climate change mitigation. A case study in northern Spain. *Urban For. Urban Green* **40**, 145–151 (2019).
- Nowak, D. J., Greenfield, E. J., Hoehn, R. E. & Lapoint, E. Carbon storage and sequestration by trees in urban and community areas of the United States. *Environ. Pollut.* **178**, 229–236 (2013).
- Vaccari, F. P., Gioli, B., Toscano, P. & Perrone, C. Carbon dioxide balance assessment of the city of Florence (Italy), and implications for urban planning. *Landsc. Urban Plan.* **120**, 138–146 (2013).
- Hardiman, B. S. et al. Accounting for urban biogenic fluxes in regional carbon budgets. *Sci. Total Environ.* **592**, 366–372 (2017).
- Järvi, L. et al. Spatial Modeling of Local-Scale Biogenic and Anthropogenic Carbon Dioxide Emissions in Helsinki. *J. Geophys. Res. Atmos.* **124**, 8363–8384 (2019).
- Gordon, A., Simondson, D., White, M., Moilanen, A. & Bekessy, S. A. Integrating conservation planning and landuse planning in urban landscapes. *Landsc. Urban Plan.* **91**, 183–194 (2009).
- Hermoso, V., Salgado-Rojas, J., Lanzas, M. & Álvarez-Miranda, E. Spatial prioritisation of management for biodiversity conservation across the EU. *Biol. Conserv.* **272**, 109638 (2022).
- Jalkanen, J., Vierikko, K. & Moilanen, A. Spatial prioritization for urban Biodiversity Quality using biotope maps and expert opinion. *Urban For. Urban Green.* **49**, 126586 (2020).
- Pickett, S. T. A., Cadenasso, M. L., Childers, D. L., McDonnell, M. J. & Zhou, W. Evolution and future of urban ecological science: ecology in, of, and for the city. *Ecosyst. Heal. Sustain.* **2**, e01229 (2016).
- Bryan, B. A., Raymond, C. M., Crossman, N. D. & King, D. Comparing spatially explicit ecological and social values for natural areas to identify effective conservation strategies. *Conserv. Biol.* **25**, 172–181 (2011).
- Regan, H. M., Davis, F. W., Andelman, S. J., Widyana, A. & Freese, M. Comprehensive criteria for biodiversity evaluation in conservation planning. *Biodivers. Conserv.* **16**, 2715–2728 (2007).
- Sarkar, S. et al. Biodiversity Conservation Planning Tools: Present Status and Challenges for the Future. *Annu. Rev. Environ. Resources.* **31**, 123–159 (2006).
- Feest, A., Aldred, T. D. & Jedamzik, K. Biodiversity quality: A paradigm for biodiversity. *Ecol. Indic.* **10**, 1077–1082 (2010).
- Jalkanen, J., Toivonen, T. & Moilanen, A. Identification of ecological networks for land-use planning with spatial conservation prioritization. *Landsc. Ecol.* **35**, 353–371 (2020).
- Newton, P. A., Oldekop, J., Brodnig, G., Karna, B. K. & Agrawal, A. Carbon, biodiversity, and livelihoods in forest commons: synergies, trade-offs, and implications for REDD+. *Environ. Res. Lett.* **11**, 44017 (2016).
- Onaindia, M., Fernández de Manuel, B., Madariaga, I. & Rodríguez-Lozano, G. Co-benefits and trade-offs between biodiversity, carbon storage and water flow regulation. *For. Ecol. Manage.* **289**, 1–9 (2013).
- Knight, A. T. et al. Knowing but not doing: Selecting priority conservation areas and the research-implementation gap. *Conserv. Biol.* **22**, 610–617 (2008).
- Brunson, M. A *definition of 'social acceptability' in ecosystem management United States Department of Agriculture Forest Service General Technical Report*. (1996).
- Bennett, N. J. Using perceptions as evidence to improve conservation and environmental management. *Conserv. Biol.* **30**, 582–592 (2016).
- Richter, I. et al. Building bridges between natural and social science disciplines: a standardized methodology to combine data on ecosystem quality trends. *Philos. Trans. R. Soc. B Biol. Sci.* **377**, 20210487 (2022).
- Raymond, C. M. et al. Inclusive conservation and the Post-2020 Global Biodiversity Framework: Tensions and prospects. *One Earth* **5**, 252–264 (2022).
- Estévez, R. A., Anderson, C. B., Pizarro, J. C. & Burgman, M. A. Clarifying values, risk perceptions, and attitudes to resolve or avoid social conflicts in invasive species management. *Conserv. Biol.* **29**, 19–30 (2015).
- Brown, G. et al. Integration of social spatial data to assess conservation opportunities and priorities. *Biol. Conserv.* **236**, 452–463 (2019).
- Verheij, J. & Corrêa Nunes, M. Justice and power relations in urban greening: can Lisbon's urban greening strategies lead to more environmental justice? *Local Environ.* **26**, 329–346 (2021).
- Termansen, M. et al. Chapter 3: The potential of valuation. in *Methodological Assessment Report on the Diverse Values and Valuation of Nature of the Inter-governmental Science-Policy Platform on Biodiversity and Ecosystem Services*. (Balvanera, P., Pascual, U., Christie, M. & Baptiste, B. eds.) (IPBES Secretariat, 2022). <https://www.ipbes.net/the-values-assessment>.
- Brown, G., Reed, P. & Raymond, C. M. Mapping place values: 10 lessons from two decades of public participation GIS empirical research. *Appl. Geogr.* **116**, 102156 (2020).
- Raymond, C. M., Kenter, J., Turner, N. & Alexander, K. Comparing instrumental and deliberative paradigms underpinning the assessment of social values for cultural ecosystem services. *Ecol. Econ.* **107**, 145–156 (2014).
- Karimi, A., Brown, G. & Hockings, M. Methods and participatory approaches for identifying social-ecological hotspots. *Appl. Geogr.* **63**, 9–20 (2015).
- Whitehead, A. L. et al. Integrating Biological and Social Values When Prioritizing Places for Biodiversity Conservation. *Conserv. Biol.* (2014). <https://doi.org/10.1111/cobi.12257>.
- Kangas, K. et al. Land use synergies and conflicts identification in the framework of compatibility analyses and spatial assessment of ecological, socio-cultural and economic values. *J. Environ. Manage.* **316**, 115174 (2022).
- Lampinen, J. et al. Envisioning carbon-smart and just urban green infrastructure. *Urban For. Urban Green* **75**, 127682 (2022).
- Network Nature. The proposed EU Nature Restoration Law: what role for cities and regions? *Policy Brief* <https://networknature.eu/sites/default/files/uploads/networknature-policy-brief-v03.pdf> (2022).
- Eggermont, H. et al. Nature-based Solutions: New Influence for Environmental Management and Research in Europe. *GAIA - Ecol. Perspect. Sci. Soc.* **24**, (2015). <https://doi.org/10.14512/gaia.24.4.9>.
- Ershad Sarabi, S., Han, Q. L., Romme, A. G., de Vries, B. & Wendling, L. Key Enablers of and Barriers to the Uptake and Implementation of Nature-Based Solutions in Urban Settings: A Review. *Resources* **8** at (2019). <https://doi.org/10.3390/resources8030121>.
- City of Helsinki. *About the City*. <https://welcome.helsinki/about-the-city-of-helsinki/#5f9de557> (2022).
- EEA. *Who benefits from nature in cities? Social inequalities in access to urban green and blue spaces across Europe*. (2022).
- City of Helsinki. *City of Helsinki Biodiversity Action Plan 2021–2028*. https://www.hel.fi/static/liitteet/kaupunkiymparisto/julkaisut/julkaisut/HNH-2035/Carbon_neutral_Helsinki_Action_Plan_1503019_EN.pdf (2021).
- City of Helsinki. *The Carbon-neutral Helsinki 2035 Action Plan*. https://www.hel.fi/static/liitteet/kaupunkiymparisto/julkaisut/julkaisut/HNH-2035/Carbon_neutral_Helsinki_Action_Plan_1503019_EN.pdf (2018).
- Hautamäki, R. Contested and constructed greenery in the compact city: A case study of Helsinki City Plan 2016. *J. Landsc. Archit.* **14**, 20–29 (2019).
- Hannikainen, M. O. Planning a Green City: The Case of Helsinki, 2002–2018 BT - Planning Cities with Nature: Theories, Strategies and Methods. in (eds. Lemes de Oliveira, F. & Mell, I.) 121–134 (Springer International Publishing, 2019). https://doi.org/10.1007/978-3-030-01866-5_9.

46. City of Helsinki. *Management of forests*. <https://www.hel.fi/helsinki/fi/asuminen-jaymparisto/luonto-ja-viheralueet/hoito/metsien/> (2022).
47. Fagerholm, N. et al. Analysis of pandemic outdoor recreation and green infrastructure in Nordic cities to enhance urban resilience. *npj Urban Sustain* **2**, 25 (2022).
48. Vierikko J; Niemelä, J; Jalkanen, J; Tamminen, N, K. S. Helsingin *kestävä viher-rakenne: Miten turvata kestävä viherrakenne ja kaupunkiluonnon monimuotoisuus tiivistyvässä kaupunkirakenteessa - kaupunkiekologinen tutkimusraportti. OP- at* <http://hdl.handle.net/10138/153476> (2014).
49. Folkard-Tapp, H., Banks-Leite, C. & Cavan, E. L. Nature-based Solutions to tackle climate change and restore biodiversity. *J. Appl. Ecol.* **58**, 2344–2348 (2021).
50. Pettorelli, N. et al. Time to integrate global climate change and biodiversity science-policy agendas. *J. Appl. Ecol.* **58**, 2384–2393 (2021).
51. Pressey, R. L. & Bottrill, M. C. Opportunism, threats, and the evolution of systematic conservation planning. *Conserv. Biol.* **22**, 1340–1345 (2008).
52. Pineda-Pinto, M. et al. Planning Ecologically Just Cities: A Framework to Assess Ecological Injustice Hotspots for Targeted Urban Design and Planning of Nature-Based Solutions. *Urban Policy Res.* **40**, 206–222 (2022).
53. Korpilo, S., Kaaronen, R. O., Olafsson, A. S. & Raymond, C. M. Public participation GIS can help assess multiple dimensions of environmental justice in urban green and blue space planning. *Appl. Geogr.* **148**, 102794 (2022).
54. Raymond, C. M., Gottwald, S., Kuoppa, J. & Kyttä, M. Integrating multiple elements of environmental justice into urban blue space planning using public participation geographic information systems. *Landsc. Urban Plan.* **153**, 198–208 (2016).
55. Brown, G. et al. The influence of sampling design on spatial data quality in a geographic citizen science project. *Trans. GIS.* **23**, 1184–1203 (2019).
56. Grabowski, Z. J., McPhearson, T. & Pickett, S. T. A. Transforming US urban green infrastructure planning to address equity. *Landsc. Urban Plan.* **229**, 104591 (2023).
57. City of Helsinki. *Statistical Yearbook of Helsinki*. <https://www.hel.fi/uutiset/en/kaupunginkanslia/statistical-yearbook-of-helsinki-2021-has-been-published> (2021).
58. Järvi, L., Grimmond, C. S. B. & Christen, A. The Surface Urban Energy and Water Balance Scheme (SUEWS): Evaluation in Los Angeles and Vancouver. *J. Hydrol.* **411**, 219–237 (2011).
59. Ward, H. C., Kotthaus, S., Järvi, L. & Grimmond, C. S. B. Surface Urban Energy and Water Balance Scheme (SUEWS): Development and evaluation at two UK sites. *Urban Clim.* **18**, 1–32 (2016).
60. Strömberg, J. *StromJan/Raster4H: Final version (Version v1.1)*. at (2020).
61. Urbanski, S. et al. Factors controlling CO₂ exchange on timescales from hourly to decadal at Harvard Forest. *J. Geophys. Res.* **112**, (2007). <https://doi.org/10.1029/2006jg000293>.
62. Järvi, L. et al. The urban measurement station SMEAR III: Continuous monitoring of air pollution and surface-atmosphere interactions in Helsinki, Finland. *Boreal Environ. Res.* **14**, 86–109 (2009).
63. Havu, M., Lee, H. S., Soininen, J. & Järvi, L. *Spatial variability of biogenic CO₂ flux in Helsinki in 2020 (version 1)*. <https://zenodo.org/record/7198140#.Y9tQFnZBw2w> (2020).
64. Muñoz Sabater, J. *ERAS-Land hourly data from 1981 to present*. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). <https://doi.org/10.24381/cds.e2161bac> (2019).
65. Dillman, D. A., Smyth, J. D. & Christian, L. M. *Internet, phone, mail, and mixed mode surveys: The tailored design method, 4th ed.* (John Wiley & Sons Inc., 2014).
66. Lechner, A. M., Stein, A., Jones, S. D. & Ferwerda, J. G. Remote sensing of small and linear features: Quantifying the effects of patch size and length, grid position and detectability on land cover mapping. *Remote Sens. Environ.* **113**, 2194–2204 (2009).
67. Lehtomäki, J. & Moilanen, A. Methods and workflow for spatial conservation prioritization using Zonation. *Environ. Model. Softw.* **47**, 128–137 (2013).
68. Agency, E. E. *Urban Atlas LCLU 2018*. <https://land.copernicus.eu/local/urban-atlas/urban-atlas-2018> (2021).

69. Official Statistics of Finland (OSF). Structure of Earnings [e-publication]. ISSN=1799-0092. Helsinki: Statistics Finland [referred: 29.8.2022]. http://www.stat.fi/til/pra/index_en.html (2022).

ACKNOWLEDGEMENTS

This study has been supported by the Tiina and Antti Herlin Foundation (grant no. 20200027), the Academy of Finland (grant nos. 321527, 325549, 337549, and 337552), and the Strategic Research Council (SRC) established within the Academy of Finland (grant nos. 335201, 335203 and 335204). Project title: Individuals, communities and municipalities mitigating climate change by carbon smart green space (CO-CARBON).

AUTHOR CONTRIBUTIONS

C.M.R. developed conceptual approach and led the writing of most sections of the paper. A.L. conducted the spatial overlap analyses and contributed to methods section. M.H. collected and analysed the flux data. J.J. collected and analysed the biodiversity data. J.L. and O.G.A. collected the SV data and wrote parts of the methods section and introduction. A.S.O. and N.G. helped write the introduction and led the writing of the study context section. A.K., L.B. and L.K. helped collect the carbon flux data and analyse the results. L.J. is the leader of the CO-CARBON project and helped write the carbon flux modelling methods and conducted the literature review linked to carbon sequestration.

COMPETING INTERESTS

The authors declare no competing interests.


ADDITIONAL INFORMATION

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s42949-023-00103-2>.

Correspondence and requests for materials should be addressed to Christopher M. Raymond.

Reprints and permission information is available at <http://www.nature.com/reprints>

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

 **Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit <http://creativecommons.org/licenses/by/4.0/>.

© The Author(s) 2023