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Analysis

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Contribution of prioritized urban nature-based solutions allocation to carbon neutrality

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Nature-based solutions (NBS) are essential for carbon-neutral cities, yet how to effectively allocate them remains a question. Carbon neutrality requires city-led climate action plans that incorporate both indirect and direct contributions of NBS. Here we assessed the carbon emissions mitigation potential of NBS in European cities, focusing particularly on commonly overlooked indirect pathways, for example, human behavioural interventions and resource savings. Assuming maximum theoretical implementation, NBS in the residential, transport and industrial sectors could reduce urban carbon emissions by up to 25%. Spatially prioritizing different types of NBS in 54 major European Union cities could reduce anthropogenic carbon emissions by on average 17.4%. Coupling NBS with other existing measures in Representative Concentration Pathway scenarios could reduce total carbon emissions by 57.3% in 2030, with both indirect pathways and sequestration. Our results indicate that carbon neutrality will be near for some pioneering cities by 2030, while three can achieve it completely.

Phasing out fossil energy from transport, heating and cooling and other major emitting processes is key to achieving carbon-neutral cities[1,2]. However, an issue often overlooked in energy systems and environmental engineering is how to spatially organize and use nature-based solutions (NBS), which can play a critical role in addressing the causes and consequences of climate change[3,4]. In terms of reducing carbon emissions, most attention has been paid to the direct effects, that is, carbon sequestration in vegetation, soil[5] and wetlands[6]. However, it is estimated that carbon sequestration can offset only a limited proportion of total anthropogenic carbon emissions, especially in urban settings[7]. To understand the full climate neutrality potential of NBS, comprehensive impacts should be estimated and quantified, including direct and indirect impacts on social and economic systems[8].

Carbon emissions mitigation through NBS involves ecosystem services and green infrastructure (GI) approaches that support human wellbeing, saving resources and costs, and sequestering carbon emitted from human activities[4,9]. For example, urban agriculture in combination with the greening of streetscapes can promote pro-environmental behaviours, for example, nudging local recreational bicycle trips instead of long-distance driving, while also providing educational

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and participatory opportunities that promote consumer preferences for foods and products of lower environmental impacts and carbon emissions[10,11]. Additionally, microclimate regulation, combined with the aesthetic ecosystem services of NBS, can promote cycling and walking, prevent urban sprawl, alleviate dependence on automobiles, and reduce heating and cooling load[12–14]. When all benefits are considered, NBS can contribute much more to urban climate neutrality goals than mere carbon sequestration effects.

Cities are ideal experiment and innovation hubs for technologies, instruments and policies for carbon neutrality[15]. For example, the European Union (EU) has pledged to decrease net emissions by 57% by 2030 (compared with 1990 levels), with the inclusion of land-use and carbon sequestration goals[16]. This climate action is to be led by 100 cities in EU member states that have pledged to achieve climate neutrality by 2030 (ref. 17). At the same time, the use of NBS is in line with EU climate policy and goals for addressing the challenges of climate change[18]. However, the current policy programme does not address or identify opportunities for NBS to mitigate carbon emissions beyond direct sequestration. Moreover, due to the limited land resources in cities, the spatial allocation and configuration of urban NBS need to be optimized to achieve maximum carbon emissions reductions.

In this Analysis, we assessed and quantified five potential carbon emissions reduction mechanisms for different types of NBS in EU cities. On the basis of sector-wise carbon emissions and the local context of 54 major European cities, we spatially allocated these five categories of NBS to each city and estimated the emissions reduction potential for each sector and city. One NBS implementation was allocated on each land use grid (30 m × 30 m) but could be functional in different categories (that is, GI that saves energy consumption while also functioning as carbon sequestration). We then compared the estimated emissions reduction potential against the 2030 climate neutrality targets of the 54 cities, to assess the potential contributions of prioritized NBS to these targets.

Multiple pathways of urban NBS to reduce carbon emissions

We first identified types of NBS linked to the effects and mechanisms of carbon emissions reduction. From established definitions of NBS in the literature[19–21], we identified major mechanisms by which NBS can mitigate carbon emissions, namely saving resources and costs, reducing urban sprawl, promoting pro-environment behaviour, microclimate regulation and carbon sequestration. Based on how recognized NBS implementations are linked to each of these carbon emissions mitigation mechanisms, we selected five types of NBS (GI, street trees and green pavements, urban green spaces and agriculture, habitat preservation and remediation, and green buildings), as they were assessed as having the closest links to the five selected carbon emissions mitigation mechanisms (connections between NBS implementations and the mechanisms are shown in Supplementary Material 2 Table A2.3). Carbon sequestration and saving resources and costs are more direct carbon emissions reduction mechanisms, for example, via carbon sequestration from urban trees and energy saving from using GI for stormwater treatment. Promoting pro-environmental behaviour generally reduces carbon emissions through indirect pathways, which are enabled by ecosystem services such as microclimate regulation, recreational opportunities and aesthetic nature experiences during daily routines. For example, microclimate regulation by GI can reduce heating and cooling demand, and hence energy use, in residential and industrial buildings[22]. This may simultaneously result in more walking, cycling and other pro-environmental habits that replace automobile driving, owing to the improved outdoor recreational opportunities and aesthetic nature experiences.

High potential for mitigation was offered by the various NBS implementations considered (Fig. 1). In all sectors, our estimates showed that NBS implementation can reduce urban carbon emissions from the spatial unit of its implementation (30 m × 30 m land use grid) by up to 25%. In the transport sector, carbon emissions can be reduced by up to 1.4% by improving streetscape design (that is, improving street greening design, narrower roads), as well as improving accessibility to urban parks and agriculture to create more agreeable environments for walking and cycling in urban centres[23], and thus reducing the need for automobile travel, and associated carbon emissions from fuel combustion[24]. The potential for carbon sequestration can sometimes be quite substantial in some cases such as the Swedish capital Stockholm[25]. In the residential sector, urban parks and agriculture can have the strongest effects in promoting pro-environmental habits, including less driving, sustainable consumption, and reduced heating and cooling demand, thus reducing carbon emissions by up to 6.2% (ref. 26). In rural and suburban areas, strict land use policy that includes habitat preservation and remediation and GI as instruments can limit large-scale, single-family residential development and save 6% of carbon emissions[27]. In industrial areas, NBS regulating microclimate and direct sequestration are the most effective emissions mitigation strategies. Green building measures can achieve both effects and reduce industrial carbon emissions by up to 18% (ref. 28). When the co-benefits of mitigating carbon emissions in different sectors and spatial locations are taken into account, the effectiveness of each urban NBS implementation can be even higher, with examples presented in Supplementary Material 4.

Spatial allocation of prioritized NBS implementation

We selected 54 cities across Europe to model prioritized spatial allocation of NBS implementations in order to maximize the carbon emissions reductions. The cities are all EU member states (as of 2022) and were selected because large amounts of consistent data are available for their home countries through the European Commission and other EU bodies (Fig. 2). The selection criteria included having a diversity of nations represented and a range of socioeconomic importance (that is, being capital cities or with high population and land area). Details of the selection criteria are provided in Supplementary Material 1.

The NBS implementations were spatially allocated on the basis of two major factors. The first of these was sectoral carbon emission sources identified within each city's land use grid. Based on the estimated potential of each NBS, the implementations were allocated to the cell with the strongest identified emission sources in each sector. The second factor was the local context of each city and each location, including socioeconomic characteristics (population density, economic activities and location in the city centre), built environment (such as current access to local parks, road density and presence of manufacturing industries) and land use structure (type, mix and intensity). For example, street trees and green pavements as an NBS to promote walking and cycling should ideally be located along city roads in high-density urban areas, while preserved habitats should be located at the urban fringe where new urban developments are likely to occur. NBS types found to be most effective in reducing emissions in the respective sector during the systematic review were prioritized for allocation in the land-use grid according to the intensity of emissions from each sector. Although the allocation of prioritized NBS was mainly based on narratives of how different NBS fit with different socioeconomic contexts and their estimated emissions mitigation effects from the literature, some basic principles needed to be applied so that allocations for the 54 cities could be performed systematically. Details of these principles, the underlying criteria and narratives of the NBS allocation process can be found in Supplementary Material 2 Table A2.4.

In prioritized NBS ($\mathrm{NBS}^{\mathrm{P}}$), we varied the spatial allocation of different NBS types to match emissions differences between the cities (Fig. 3). In cities with large industrial areas and also ample natural areas (mainly central and eastern European cities, for example, Zagreb, Bucharest and Stuttgart), urban forests through habitat preservation

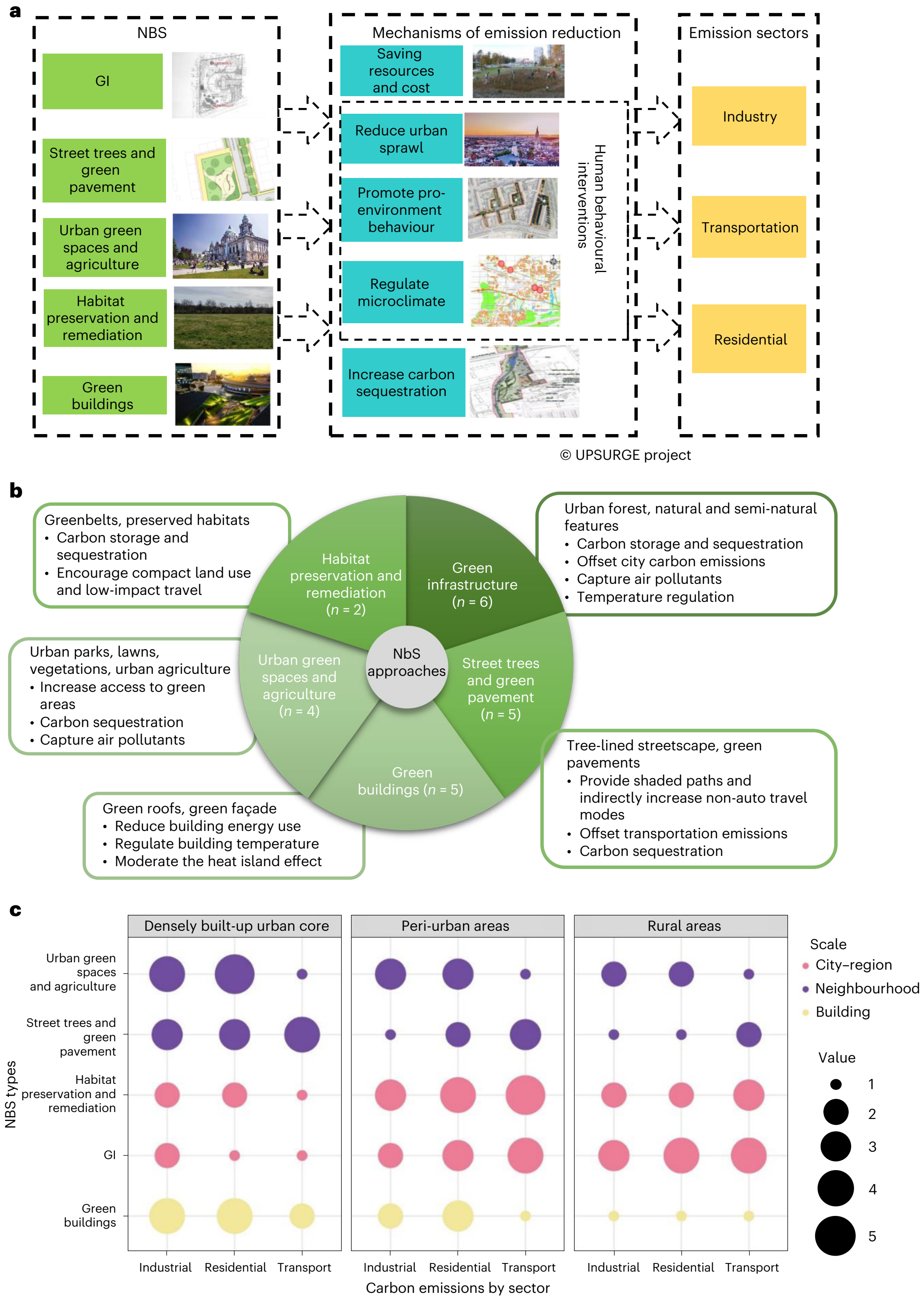

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Fig. 1 | Meta-analysis summary of potential pathways and effects of NBS to reduce urban carbon emissions. a, Potential pathways of NBS to reduce emissions. **b**, Key NBS approaches and their contribution to carbon neutrality. *n* is the number of articles reviewed. **c**, Summary of NBS impact evaluations.

were mostly allocated to the natural areas. Another type of habitat preservation, greenbelts, which have stronger effects in limiting urban sprawl, was allocated to the urban fringe of many major and growing cities across Europe, including Warsaw, Barcelona, Cologne, Helsinki and Marseille. Road greening through street trees was allocated to the urban fringe of cities that are currently characterized by low-density development and high level of car-based commuting, including Rome, Athens, Naples, Valletta, Copenhagen, Helsinki and Stockholm. Urban

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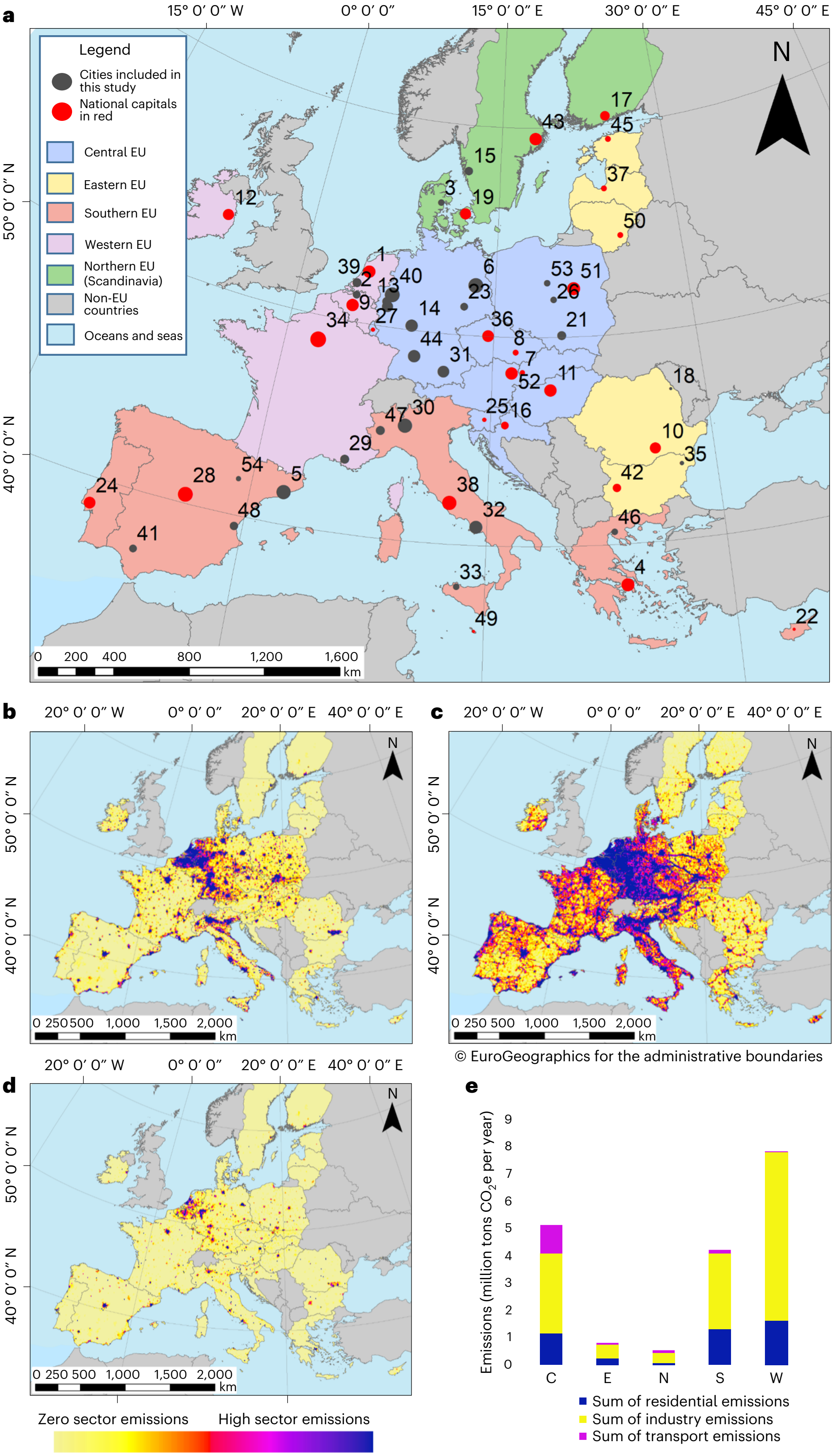

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Fig. 2 | Location and carbon emission distributions of the 54 selected EU cities. **a**, Locations of the cities (the numbers representing cities are listed in Supplementary Material 1 Fig. A1.1). **b**, Residential emission distribution. **c**, Transport emission distribution. **d**, Industrial carbon distribution. **e**, Regional carbon emissions across different parts of the EU.

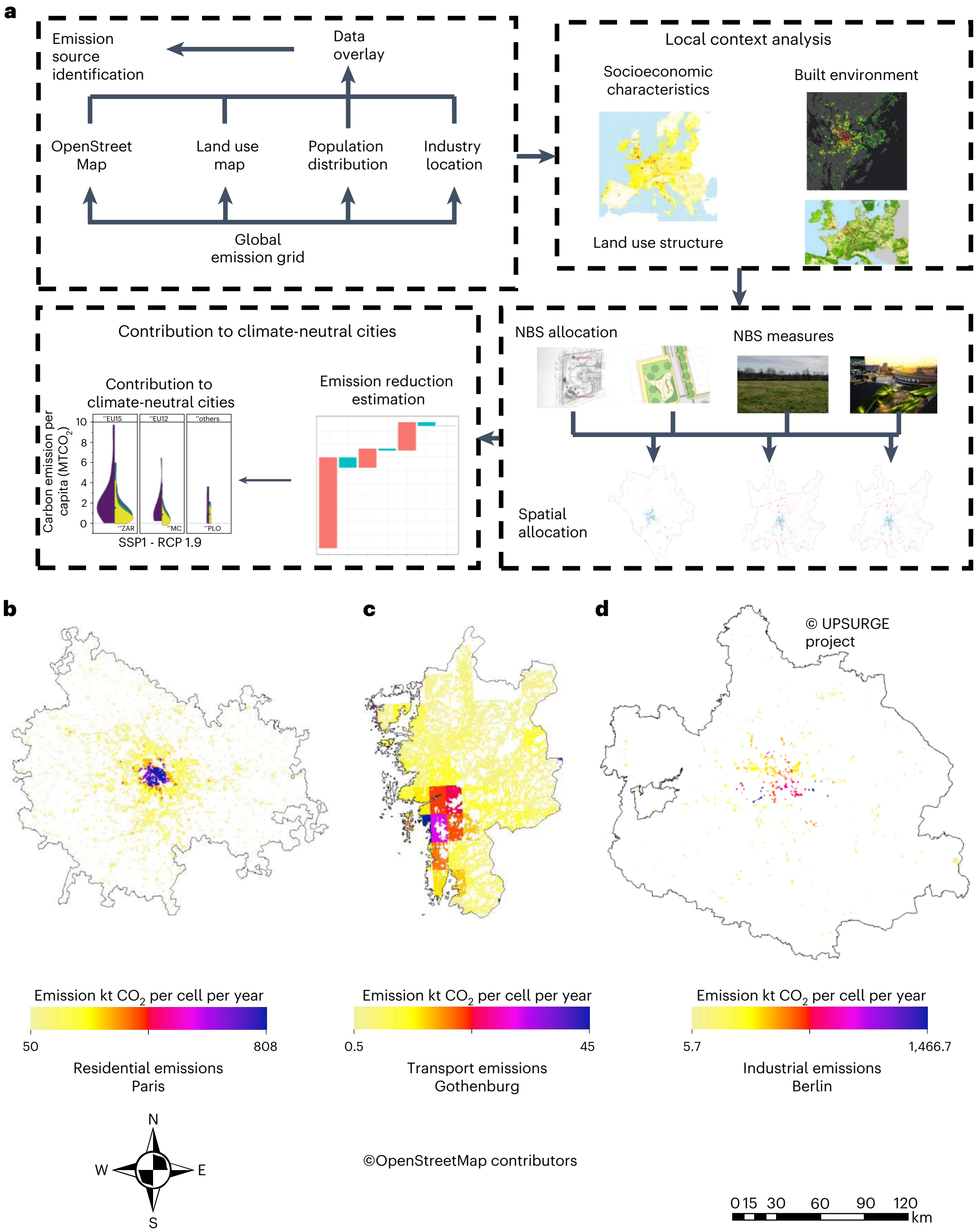

Fig. 3 | Modelling framework used for allocation of NBS implementations. a, The allocation process of NBS implementations. **b**, Residential emission source identification for Paris. **c**, Transport emission source identification for Gothenburg. **d**, Industrial emission source identification for Berlin.

parks and agriculture can simultaneously reduce carbon emissions and improve the wellbeing of urban residents, so these NBS^P were prioritized in southern and eastern European cities. The spatial allocations included improving green access through urban parks in urban centres in Barcelona and Lasi, and improving green access through urban parks and agriculture in the urban fringe in Zagreb, Naples, Lodz, Valletta and Włocławek. Many southern and eastern European cities with high residential emissions and high population density were co-allocated green access and green buildings. Co-allocated green buildings and road greening were considered the most effective implementations in denser and more developed cities, mainly western European cities. Six typical cities are selected for presentation of different prioritizations of NBS allocations based on their emission patterns (Fig. 4).

Contribution of NBS to carbon emissions reduction in cities

If NBS^P implementations were to be introduced in practice, they could prevent large proportions of carbon emissions from different sectors. For all cities, NBS^P could reduce total carbon emissions by on average 17.4%, with 8.1% in the residential sector, 14.0% in the industrial sector

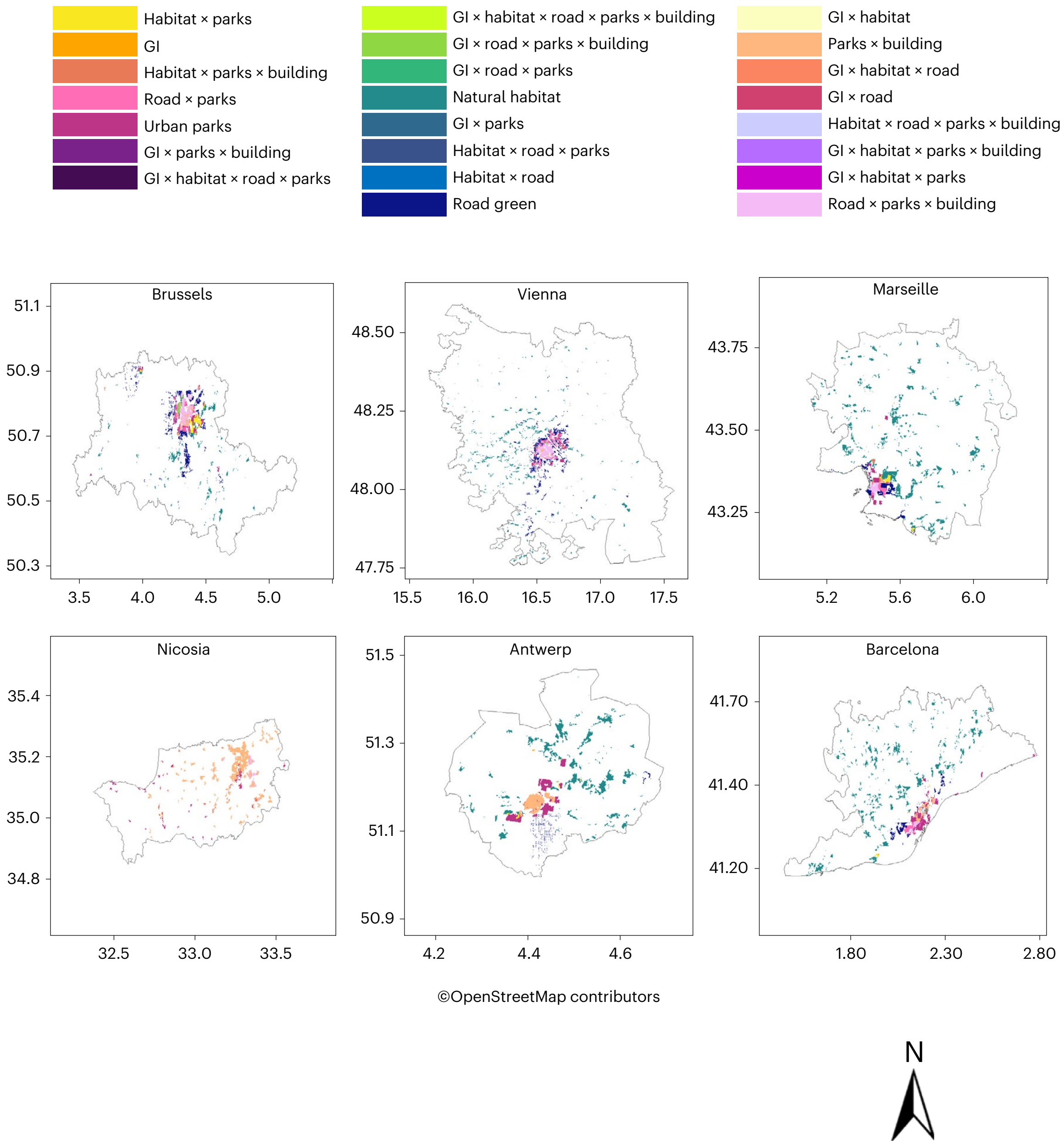

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Fig. 4 | Examples of spatial allocation of prioritized NBS implementations in six of the selected European cities. Allocations for all 54 EU cities are shown in Supplementary Material 1 Fig. A1.2. The coordinate grid is shown alongside each map, with *x* axis and *y* axis showing the longitude and latitude, respectively, of World Geodetic System 1984 (WGS84).

and 9.6% in the transport sector. Of the remaining carbon emissions, 5.6% could be compensated for by carbon sequestration. The largest emissions reductions would occur in the industrial sector, with GI contributing most to the effect as it can save resources (water, energy and building materials) and reduce maintenance costs associated with industrial buildings. The residential sector has the lowest potential for NBS-related emissions reductions, as green buildings are usually limited in size and carbon sequestration potential is limited by space constraints in residential blocks. Moreover, green buildings are less effective in certain parts of the EU with lower cooling potential (that is, northern EU). Note that some of the carbon sequestration effects of some NBS^{P} implementations (mainly urban forests and parks) allocated on existing natural areas may already have been captured by existing vegetation, while for NBS^{P} that reduce anthropogenic carbon emissions through indirect pathways, our estimated emission reductions are almost additional even though some vegetation is already in place. Detailed explanations of the spatial allocation of NBS^{P} can be found in Methods.

The carbon emissions saving of NBS^{P} was found to vary between the different cities and regions, with the results for 15 typical cities presented in Table 1. The highest carbon emissions reduction potential was found for eastern EU cities, where NBS^{P} could reduce total carbon emissions by 20.3%, closely followed by northern EU (18.2%). The lowest carbon emissions reduction potential identified was in western European cities, closely followed by central EU cities, where NBS^{P} could reduce total carbon emissions by 13.0% and 13.2%, respectively. The differences between cities in emissions reduction potential were largely attributable to differences in carbon sequestration potential. Among the remaining emissions reduction potential following NBS^{P} implementation in the three sectors, carbon sequestration could offset 47.6% and 10.7% of the carbon emissions in northern and eastern EU cities, but only 6.7% in central European cities. As consistent with previous studies[7],

Table 1 | Main NBS types and carbon emission reduction effects of highlighted cities. Carbon emissions levels according to Global Carbon Grid data and the main NBS type that should be prioritized in different sectors in 15 typical European cities to maximize emissions reduction potential

City	Residential emissions share	Industrial emissions share	Transport emissions share	Total emissions per capita (tons per year)	Emissions reduction rate (resident)	Emissions reduction rate (industry)	Emissions reduction rate (transport)	Emissions reduction through carbon sequestration	Main NBS type
Paris	53%	30%	17%	7.34	6%	26%	15%	1%	GI and green buildings
Madrid	28%	35%	36%	5.06	7%	18%	15%	2%	Habitat and GI
Berlin	38%	30%	33%	7.55	6%	13%	14%	4%	Urban green spaces and green buildings
Milan	40%	39%	21%	7.12	12%	14%	15%	0%	GI and green buildings
Rome	36%	30%	34%	6.07	5%	8%	12%	2%	Urban green spaces and green buildings
Warsaw	35%	30%	35%	5.31	5%	5%	14%	3%	Urban green spaces and green buildings
Athens	38%	28%	34%	3.98	3%	3%	14%	4%	Urban green spaces and green buildings
Vienna	23%	21%	56%	5.92	9%	10%	13%	13%	Urban green spaces and habitat
Stockholm	20%	18%	62%	1.7	4%	5%	12%	55%	Street trees and urban green spaces
Budapest	32%	33%	36%	5.61	8%	8%	13%	2%	GI and green buildings
Brussels	42%	29%	29%	10.66	10%	13%	14%	1%	Urban green spaces and habitat
Amsterdam	27%	35%	37%	6.69	10%	11%	8%	1%	Urban green spaces and green buildings
Prague	25%	30%	45%	5.74	7%	11%	11%	5%	Preserved habitat
Lisbon	28%	25%	47%	3.58	2%	7%	6%	2%	Street trees
Bucharest	33%	36%	31%	3.27	4%	5%	11%	0%	GI

Stockholm has a very high carbon sequestration rate (55%) for the remaining emissions, partly due to very low industrial emission density in the region, as well as large natural areas within the urban boundary.

The emissions saving potential identified for different sectors highlights the importance of considering the socioeconomic and ecosystem context when prioritizing NBS implementations to maximize emissions reductions. In terms of residential emissions, northern EU cities were found to have the lowest residential emissions saving potential through NBS$^{\mathrm{P}}$ (4.5%), while central European cities had the highest (6.8%). Northern EU cities also had the lowest industrial emissions saving potential (6.7%), while western EU cities had the highest (11.0%). This highlights the diverse pathways towards carbon neutrality in the two most developed regions in the EU. Western EU cities will need to rely on green–blue infrastructure to reduce industrial emissions, while northern EU cities will have to depend more on natural ecosystems for carbon sequestration and transport emissions reduction, as they were found to have the highest transportation emissions-saving potential (11.8%). More details of sector- and city-specific NBS$^{\mathrm{P}}$ contributions are provided in Supplementary Material 4.

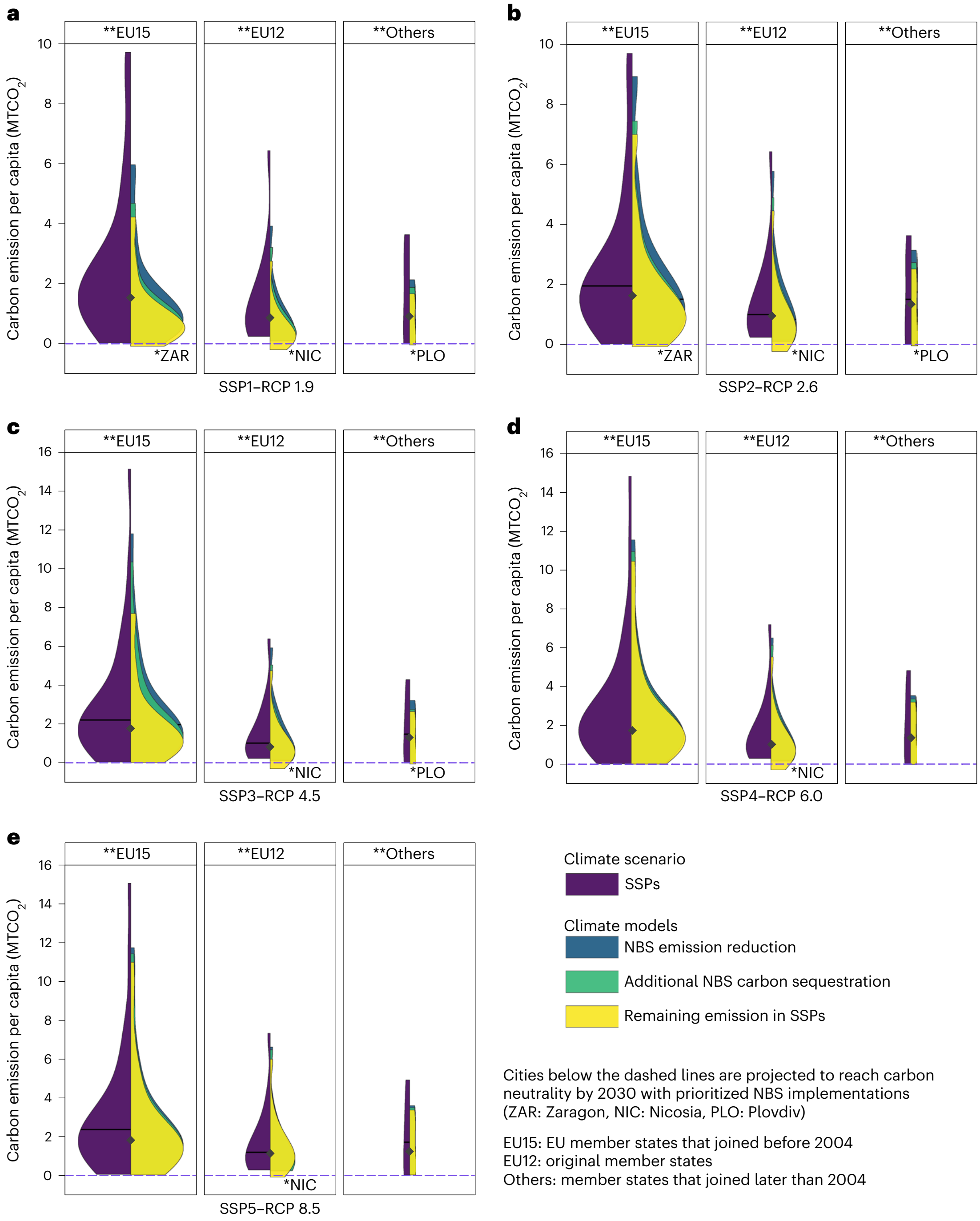
Implications for pathways to climate-neutral cities by 2030

Next, we compared the carbon emissions reductions of the different NBS strategies and the carbon sequestration potential under Shared Socioeconomic Pathways (SSPs) differing in terms of climate actions and developmental paths. NBS$^{\mathrm{P}}$ was most effective in SSP1 (Fig. 5), in which maximizing NBS implementations on all available land parcels in the Representative Concentration Pathway (RCP) 1.9 scenario would reduce total carbon emissions by on average 57.3% (95% confidence interval (CI) 47.9–66.7%) compared with the SSP1 baseline, with 22% marginal reduction by indirect pathways including human behavioural interventions by NBS compared with the RCP 1.9 scenario. NBS was least effective in SSP5, in which maximizing NBS implementations on all available land parcels in the RCP 8.5 scenario would reduce total carbon emissions by on average 16.2% (95% CI 2.7–29.7%) compared with the SSP5 baseline, with only 1.7% marginal reduction compared with the RCP 8.5 scenario. Taking carbon sequestration into consideration, maximizing NBS implementations and carbon sequestration on all available land parcels in the RCP 1.9 scenario would reduce total carbon emissions by on average 62.5% (95% CI 49.4–108.6%) compared with the SSP1 baseline, by capturing a further 13.3% of carbon emissions. Maximizing NBS implementations on all available land parcels in the RCP 8.5 scenario would reduce total carbon emissions by on average 19.9% (95% CI 0.0–65.3%) compared with the SSP5 baseline, by achieving a further 3.6% marginal reduction compared with the RCP 8.5 scenario.

The effects of targeted policies to reduce carbon emissions in the RCP scenarios were stronger for EU12 countries (original 12 EU member states), while NBS and carbon sequestration effects were stronger for EU15 countries (member states that joined before 2004). Three cities were projected to achieve carbon neutrality before 2030 with the maximized implementation of NBS and carbon sequestration. These were Nicosia (in all scenarios), Zaragoza (RCP 1.9 and RCP 2.6) and Plovdiv (RCP 1.9, RCP 2.6 and RCP 4.5). Other cities, including some pioneering cities in climate action such as Amsterdam, Copenhagen, Helsinki and Stockholm, were projected to have less than 0.5 tons of carbon emissions per capita and year by 2030, almost achieving the carbon neutrality goal.

Discussion and policy implications

Compared with carbon sequestration, the indirect effects of NBS in carbon emissions reduction through human behaviour interventions were shown to play a much larger role in reducing urban carbon emissions. In comparison with prioritized NBS implementations, carbon sequestration was found to have a lower overall potential for meeting the goal of carbon neutrality in the European cities studied. Previous studies have estimated that in the most favourable scenario, the terrestrial biosphere in the EU can sequester 6.5–8% of projected anthropogenic emissions by 2030 (ref. 29). Our novel analysis extended previous research by identifying the carbon emissions reduction potential of NBS through broader, more effective direct and indirect mechanisms (human behaviour interventions and resource and cost savings), rather than simply the carbon sequestration effects reported in other studies[30–32].



Cities below the dashed lines are projected to reach carbon neutrality by 2030 with prioritized NBS implementations (ZAR: Zaragon, NIC: Nicosia, PLO: Plovdiv)

EU15: EU member states that joined before 2004
EU12: original member states
Others: member states that joined later than 2004

Fig. 5 | Contribution of prioritized NBS to carbon neutrality in different SSPs and RCPs for EU cities. a, SSP1–RCP 1.9. **b**, SSP2–RCP 2.6. **c**, SSP3–RCP 4.5. **d**, SSP4–RCP 6.0. **e**, SSP5–RCP 8.5. MTCO$_2$, metric tons of CO$_2$.

The findings in this study have important policy implications in terms of the allocation and implementation of NBS for the goal of climate change mitigation. Successful implementation will require a much better understanding of the behavioural aspects of NBS and of the socioeconomic, industrial and cultural context of each city, and the interactions with biophysical factors. Importantly, co-benefits and hybrids to reduce emissions from multiple sectors (transport, residential and industrial) should be prioritized and targeted, through integrating fossil-free energy systems and (grey) technologies with NBS such as green access, greening of streetscapes and roads, and green buildings and GI penetrating into residential high-density urban areas. In sparser but fast-developing parts of cities and in industrial urban areas, exploiting the multi-functions of urban forests, including greenbelt and GI protection, should be prioritized.

Another policy implication relates to the 2030 policy goal of carbon-neutral cities, where more ambitious climate policies phasing out fossil fuels can seek to maximize NBS potential at the same time. Our comparisons of different RCP scenarios revealed that policy pathways with more ambitious emissions reduction measures and targets (for example, RCP 1.9 and RCP 2.6) were positively correlated with greater NBS implementation. More ambitious climate policies preserve more natural land, protect ecosystem quality, and promote high-density and compact urban development, which all present opportunities for spatial allocation of more implementations to maximize NBS potential.

Thus, pioneering cities that have created the best opportunities for NBS to be effective should extend their climate action plans to fully incorporate NBS implementations, which would maximize their chances of achieving city carbon neutrality. Inspired by how other environmental pollutants have been successfully handled in the past[25], we end by suggesting that the EU Commission should implement NBS-based spatial urban planning as a key strategy to achieve carbon-neutral cities.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-023-01737-x.

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Methods

We applied a four-step approach in estimating and projecting the contributions of NBS to the climate-neutral goals of the 54 EU cities. First, we conducted a systematic meta-analysis to estimate the effects of five categories of NBS implementations on carbon emissions reductions from three sectors (transport, residential and industrial), in addition to carbon sequestration. Second, we spatially allocated NBS implementations to 30 m × 30 m land use grids for each of the 54 cities. The allocation was based on carbon emission disaggregated on land-use grids, and on socioeconomic context factors for different places in each city. Third, we calculated and summarized the carbon emissions reduction potential for the NBS implementations allocated to each of the 54 cities. Finally, we compared and projected the contribution of the NBS implementations to the climate neutrality goals of the 54 European cities for 2030.

Meta-analysis of carbon emissions reduction potential of NBS

To better communicate the effects of NBS, we integrated findings from previous studies on the level of benefit of different types of NBS for carbon neutrality. We applied the qualitative meta-summary techniques proposed by Sandelowski and Barroso[33] to summarize the mechanisms proposed in the literature. Meta-summary techniques are particularly useful for this purpose as they synthesize a combination of qualitative and quantitative research findings. Researchers have approached the subject of carbon emissions mitigation through a variety of analytical methods that include statistical modelling, simulation, case studies, surveys and historical data analysis. We used the meta-summary method to (1) extract relevant statements on findings from each article; (2) reduce these statements to abstract findings that included the direction and intensity of carbon mitigation effect, and the local social and economic conditions in which these methods are applied; and (3) thematize and categorize findings into key NBS strategies that were considered in subsequent analysis.

We performed a literature search in the Web of Science database on 16 July 2022, using multiple search queries combining keywords associated with NBS and carbon emissions issues (Supplementary Material 3 Table A3.1). From the list of papers retrieved (578 articles), we eliminated those repeated between the NBS groups and selected papers by reviewing titles and abstracts to check if they: (1) focused on pathways towards zero carbon emissions (rather than/in addition to estimating the gross volumes and trends in carbon emissions); (2) assessed or quantified the efficacy of carbon emissions reduction strategies; (3) investigated NBS strategies (not non-NBS approaches such as the use of non-fossil fuel energy sources, low-carbon subsidy policies and so on); and (4) reported transferable metrics (such as percentage change, value per unit, and elasticity) that could be applied to different places.

The full text in the remaining 54 articles was reviewed against the research questions. In this selection phase, we looked for NBS interventions that involve direct mitigation (for example, climate regulation and carbon sink) or indirect mitigation (for example, interventions that could influence human behaviour towards low-carbon travel), aiming to include cases representing different NBS approaches to the greatest extent possible. We also intentionally covered research conducted in multiple countries and regions of the world. In total, 22 articles were included in the review (with the selection flow chart in Supplementary Material 3 Fig. A3.1).

The basic characteristics of the 22 studies are summarized in Supplementary Material 3 Table A3.2. One study focused on urban reforestation at a global scale, while the other studies were conducted in eight countries/regions, namely Europe ($n = 4$), China ($n = 6$), the United States ($n = 4$), Canada ($n = 3$), South Korea ($n = 2$), Japan ($n = 1$), New Zealand ($n = 1$) and Malaysia ($n = 1$). All studies were published between 2010 and 2020.

To synthesize results from different studies, a meta-analysis requires common measures of effect size. Our selected metrics were: (1) the percentage of emissions that can be offset by carbon sequestration of NBS, and (2) the carbon reduction rate, expressed as tons per hectare per year. We chose these two metrics not only because they were both widely employed in the literature, thus reducing the amount of unit conversion required, but also because they offer flexibility for evaluating carbon emission reduction effects through different mechanisms. In this study, we used percentage metrics for regional-scale sequestration effects from GI, street trees and green pavements, urban green spaces and agriculture, and habitat preservation and remediation, while using carbon reduction rate in tons per hectare per year for local-scale carbon reduction effects through direct and indirect interventions such as implementing street trees and green pavements, urban green spaces and agriculture, and green buildings. We extracted statements indicating the relationship between studied NBS and carbon reduction and synthesized the indicators to describe the impact of NBS on carbon emissions. Supplementary Material 2 Table A2.2 describes the statements from our selected studies and the location- or environment-related variables for NBS design, with the synthesized results of the average, upper and lower boundaries of carbon reduction potential for each type of NBS (Supplementary Material 2 Fig. A2.1).

There were some limitations in the NBS meta-analysis presented in this paper. First, differences in study design, participants, interventions and outcomes made it difficult to compare the results across studies. This limitation is grounded in the nature of the meta-analysis process itself, which relies on data from multiple studies and is only as good as the quality of those studies. However, inclusion of as many studies as possible worldwide is important, to mitigate any methodological issues nested in one study. Second, to provide more accurate results, future studies should examine the assumptions behind the values more critically. Criteria such as soil type, the time lag for tree growth, and carbon emissions during NBS implementation work should be included in the discussion. Third, we based our study on Europe, but drew on experiences gained in case studies in many countries outside Europe, to a large extent due to the scarcity of literature. Adapting values from one place to another proved more difficult than learning from analyses conducted within a single context. However, our aim was to provide a thorough quantitative evaluation of the carbon mitigation benefits of different types of NBS, which has not been done previously. By synthesizing data from a wide range of studies conducted in various cities around the world, some of which have similar urban densities, social structure and behavioural characteristics as European cities, we were still able to gain valuable insights into developing effective NBS strategies for European cities.

Spatial allocation of NBS implementations

Spatial allocation of the most cost-effective NBS for emissions reduction was based on sectoral carbon emissions in each land use grid (30 m × 30 m) for the transport, residential and industrial sectors in each city. Certain NBS types were considered most effective in reducing emissions in each sector, such as green buildings for residential emissions, road greening for transport emissions, and green–blue infrastructure for industrial emissions.

Global Carbon Grid (GID) data from the Global Infrastructure Emissions Database (http://gidmodel.org.cn/) were disaggregated to assess the sources of sectoral carbon emissions in each land use grid. The GID establishes 0.1° × 0.1° CO_2 emissions maps (year 2019) for six source sectors: power, industry, residential, transport, shipping and aviation[34,35]. In this study, we assessed the carbon mitigation effects of spatially allocating NBS within three sectors: industrial, residential and transport. Socioeconomic and ecosystem co-variates used to disaggregate carbon emissions into a land use grid in our study included population density, building density, land use structure, industrial and commercial units, and road networks, to enable identification of the emissions sources at a fine spatial scale. The data were acquired from EU or global data sources that are open to the public, including Urban Atlas, EuroStat and OpenStreet Map. Detailed descriptions of the data and sources are provided in Supplementary Material 2 Table A2.1. Verification of the sectoral emissions data can be found in Supplementary Material 1.

GID sectoral carbon emission data were disaggregated to the land use grid to identify the emissions sources. For transport emissions, there is a positive correlation between vehicle-kilometres travelled and road classes, and between vehicle-kilometres travelled and population density[36]. In this study, we first used binary dasymmetric mapping (road = 1, non-road = 0) to distribute emissions to roads, and then adjusted the emissions for each road segment cell by road classes and population density. Transport carbon emissions were calculated as:

$$E_t = \sum_{s=1}^{S} \frac{C_t \times E_s}{C_s} \quad (1)$$

where E_t are disaggregated to emissions source, but not adjusted, emissions in target zone t; E_s are emissions in source (large) zone s; C_t is the count of road cells in target zone t; and C_s is the count of road cells in source zone s, including motorways, primary roads and secondary roads.

The adjusted emissions for each land use grid were then calculated as:

$$e_t = E_t \times W_{\text{class}} \times W_{\text{pop}} \quad (2)$$

where e_t is the adjusted transport emissions in kt CO_2-eq per land use grid; W_{class} is the weight of road classes (we used a standardized posted speed on each road segment as a proxy and normalized the values to 0–1); and W_{pop} is the weight of population density, normalized to 0–1.

For residential emissions, we constructed a relationship between residential carbon emissions and population and building density, using population density data from EuroStat and the urban fabric density classifications (11100–11300) in the Urban Atlas database as our model inputs. The relationship took the form:

$$e_r = f(\text{Den}_{\text{pop}}, \text{Den}_{\text{building}}) \quad (3)$$

where e_r is residential emissions in kt CO_2-eq per land use grid; Den_{pop} is population density; and $\text{Den}_{\text{building}}$ is building density, normalized to 0–1.

When estimating the function $f(.)$ between residential carbon emissions and population and building density, we tested different functional forms (linear model, local polynomials and tree-based machine learning model), with a cross-validation method for model selection (70% observations as training data, 30% as test data). We found that the random forest model produced the lowest root mean square error. Thus we applied the random forest model to obtain residential CO_2 emissions estimates.

For industrial emissions, we applied binary dasymmetric mapping (industry = 1, non-industry = 0) to distribute emissions to industrial and commercial complexes that cause major carbon emissions. We used the land cover type 12100 in the Urban Atlas land use database to represent this category, which contains sites including industrial activities, major commercial sites, energy plants and sewage treatment plants. The equation for industrial carbon emissions was:

$$e_i = \sum_{m=1}^{M} \frac{C_i \times E_m}{C_m} \quad (4)$$

where e_i is industrial carbon emissions in land use grid i; E_m is carbon emissions in the original 10 m × 10 km grid m; C_i is count of industry land use grid in target zone i; and C_m is count of industry land use grid in the original 10 m × 10 km grid.

In addition to carbon emissions at the scale of land use grid, we used socioeconomic variables (population density, building density, road networks and land use structure) and biophysical variables (ecosystem services and vegetative sequestration) to determine the allocation of NBS. Socioeconomic variables were those listed in Supplementary Material 2 Table A2.1. For local ecosystem services, we used the indicator for the percentage of natural and semi-natural areas as potential GI from the ESPON GRETA report[37]. In particular, the ecosystem service of carbon sequestration potential of vegetation was identified using Corine Land Cover data from 2018, by assigning each vegetative land cover category a sequestration potential based on the empirical parameters provided by Page et al.[7]. The conditions used for determination of each NBS approach are described in details (Supplementary Material 2 Table A2.4), while their prioritized application sites are also spatially allocated (Fig. 4). The above allocation and evaluation strategies of NBS^{P} enable the most carbon emission reduced on per land use grid allocations of NBS^{P}.

Projecting NBS contributions to 2030 climate-neutral goals of European cities

We estimated the percentage of carbon emissions that could be saved by NBS for each sector (residential, industrial and transport) from the meta-analysis results (Supplementary Material 2 Fig. A2.1), with a summation of NBS implemented in each city determined by the allocation:

$$r_{l,n} = \sum_{i=1}^{I} \frac{E_{l,i} \times R_l}{E_{l,i}} \quad (5)$$

where $r_{l,n}$ is the percentage emissions reduction for sector l in city n; $E_{l,i}$ is carbon emissions from sector l in land use grid i; and R_l is the emissions reduction metrics for sector l.

Our emissions reduction metrics take into account the presence of impervious surfaces and the fact that NBS cannot practically fully cover a land-use grid. In such cases, we estimate local parameters to convert area-based metrics from the meta-analysis to the percentage of carbon reduction that can be achieved in different areas such as regions, cities and buildings. This is to account for the specific conditions of the area and to ensure that the estimated carbon reduction is appropriate for the scale of the intervention. This process is especially useful for indirect pathways and small-scale interventions such as green buildings, as the percentage of reduction effects of these approaches on residential energy use and associated carbon emissions has been well documented.

Note that the carbon sequestration effects of some NBS^{P} implementations (mainly urban forests and parks) allocated on existing natural areas (such as grasslands or forests) may have already been captured by existing vegetation. For those, habitat preservation and bio-remediation are allocated as the NBS^{P}, which can lead to an improvement in the quality of these areas in terms of both biodiversity and carbon sequestration. Meanwhile, for NBS^{P} that reduces anthropogenic carbon emissions through indirect pathways, our estimated emission reductions were almost additional even though some vegetation was already in place. For example, street trees were mainly already present around highways featuring high transportation emissions. However, improved intersection design coupled with streetscape features such as street greenery and green pavement, implemented in proximity or in parallel to the land use grid among the highest transportation emission, can promote walking and biking modal choices to mitigate intra-city vehicle travel demand.

To project how NBS would contribute to the climate neutrality goals of European cities in 2030, we conducted a comparative analysis of the percentage of carbon emissions mitigation in each city with its (emissions mitigation pathway) RCP for different SSPs. Our methodology assumed that the future trajectory of urban carbon emissions in each city is influenced by broader regional socioeconomic and environmental trends, and that emissions trajectories follow regional patterns. Based on the regional projection results of the sixth climate model intercomparison project (CMIP6) for SSP scenarios[38], we assigned each city a regional average carbon emissions change rate for different SSP baselines in different EU regions, as a proxy for future urban carbon emissions. While we acknowledge the complex and diverse urban emissions landscape in Europe, we apply this generalized method as a starting point to estimate the potential contribution of NBS to carbon emissions mitigation. We generate base carbon emissions for the EU cities and project carbon emissions corresponding to different RCPs in 2030 using these regional average carbon emissions change rates. The equation for total carbon emissions was:

$$E_{s,n} = E_{t_0,n} \times \left(1 + \frac{(E_{r_n,t_2,s} - E_{r_n,t_1,s}) \times (t_2 - t_0)}{E_{r_n,t_1,s}}\right) \quad (6)$$

where $E_{s,n}$ is the carbon emissions for SSP scenario s in city n; $E_{r_n,t,s}$ is the carbon emissions of SSP scenario s in EU region r_n in year t; r_n is the EU regional classification where the city n is located by CMIP6; and t_0, t_1 and t_2 is the starting year of the carbon emissions study, the year closest to the starting year, and the ending year of the study in CMIP6, respectively.

To calculate the carbon emissions of European cities on different SSP development paths under the effect of NBS, we summarized Shared Climate Policy Assumptions (SPA) from SSP1 to SSP5 together with their respective NBS storyline. Specifically, we translated different levels of policy stringency into varying levels of reduction of NBS and conversion of land use. Since the RCPs and SSPs already consider many mitigation activities, we needed to make sure that our analysis incorporating NBS would not involve double-counting of the mitigation policy effects. To address this issue, we generated specific NBS based on the predicted changes in SPAs for SSPs (Supplementary Material 3 Table A3.3). For example, stricter preservation of natural areas in RCPs does not consider the fact that these natural areas can provide additional effects in reducing automobile travel and residential energy consumption. On the other hand, if transportation measures of a certain RCP have already been highly featured (that is, SPA for SSP.1), we reduced the NBS effects on transportation in that scenario to avoid double-counting.

While RCP and SSP consider the net balance of carbon emissions and removals from the atmosphere, they do not directly account for carbon sequestration. Carbon sequestration can be achieved through various methods, such as bioenergy with carbon capture and sequestration (BECCS), afforestation, reforestation and soil carbon sequestration. Although some RCP and SSP scenarios include BECCS, other types of carbon sequestration may not be incorporated[39]. To fully capture the potential impact of all carbon sequestration methods on mitigating future climate change, it is essential to perform separate sequestration potential calculations. In this study, we calculated the final sequestration potential by combining the converted rate of green space area and the proportion of existing urban carbon sequestration. The equation used for mitigating carbon emissions was as follows:

$$E_{c,n} = \left(E_{t_0,n} \times \sum_{i=1}^{l} (r_{l,n} \times m_{l,r_n})\right) - S_n \times C_{r_n} \quad (7)$$

where $E_{c,n}$ is the carbon emissions for climate mitigation model c (including both NBS and carbon sequestration) in city n; m_{l,r_n} is the SPA-converted mitigation rate for emissions sector l for CMIP6 classified EU region r; S is the carbon sequestration rate; and C[0, 2] is the standardized green space change index, which measures the change in green space area in a city over time, with higher values indicating a greater increase in green space area. While predicting carbon sequestration in SSP scenarios typically involves calculating the change in vegetation through land use[40], we used a simplified approach[7] to calculate carbon sequestration change. Detailed information is provided in Supplementary Material 3.

Based on the climate mitigation model results for urban carbon emissions for both the SSP and RCP scenarios, we further elaborated per capita carbon emissions based on the respective population change projections. This enabled us to make cross-sectional comparisons of the progress made by different cities and regions in Europe towards reaching their climate neutrality goals by 2030, and the contribution of NBS to this progress.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The data that support the findings of this study are openly available in: Global Carbon Grid (http://gidmodel.org.cn/?page_id=1425), Urban Atlas via Copernicus (https://land.copernicus.eu/local/urban-atlas/urban-atlas-2018), EuroStat (https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/population-distribution-demography/geostat), OpenStreet Map (https://www.openstreetmap.org/#map=5/62.994/17.637), European Commission (https://data.jrc.ec.europa.eu/dataset/jrc-luisa-ui-boundaries-fua) and SSP IAM scenarios (https://tntcat.iiasa.ac.at/SspDb/).

Code availability

The source code used in this study is publicly available on GitHub at https://github.com/ccong2/NbS. The repository contains the implementation of emission disaggregation and NBS spatial allocation described in this paper and all necessary scripts for creating NBS impact evaluation figures. The code is written in R and is released with 8114988.

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Author contributions

H.P.: writing—original draft preparation, conceptualization and validation; J.P.: data curation, methodology, validation and investigation; R.S.: data curation, software and visualization; C.C.: writing—original draft preparation, methodology, software, conceptualization and visualization; Z.C.: writing—original draft preparation, data curation, methodology and visualization; S.B.: supervision, writing—reviewing and editing, and conceptualization; P.T.: supervision and writing—reviewing and editing; J.C.: supervision and writing—reviewing and editing; Z.K.: writing—reviewing and editing, conceptualization and supervision.

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Competing interests

The authors declare no competing interests.

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Reporting Summary

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Software and code

Policy information about availability of computer code

Data collection	Data are directly obtained from public database listed in the study.
Data analysis	Data were analyzed and visualized with the open-source statistical software R 4.1.3, the libraries ggplot2 3.4.0, origin 2022b and ArcMap 10.8.2 under the organization license of Shanghai Jiao Tong University and KTH Royal Institute and Technology.

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[Global Carbon Grid] at http://gidmodel.org.cn/?page_id=1425;
[Urba Atlas via Copernicus] at https://land.copernicus.eu/local/urban-atlas/urban-atlas-2018;

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Human research participants

Policy information about studies involving human research participants and Sex and Gender in Research.

Reporting on sex and gender	This information has not been collected.
Population characteristics	see above
Recruitment	Not relevant to our study.
Ethics oversight	Not relevant to our study.

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

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Ecological, evolutionary & environmental sciences study design

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Study description	The study uses the nature-based solutions (NbS) to analyze 54 major European cities' carbon mitigation capacity, including human behavior interventions, resource conservation and carbon sequestration. For each city in 2030, the study compares its mitigation of carbon emissions with its representative concentration pathway (RCP) under various shared socioeconomic pathways (SSP) to predict how NbS will contribute to the climate neutrality goals of European cities in 2030.
Research sample	The study includes 54 cities across Europe to model where NbS implementations should be spatially allocated to maximize the carbon emissions reductions. The cities are all in European Union (EU) member states (as of 2022) and were selected because large amounts of consistent data are available for their home countries through the European Commission and other EU bodies.
Sampling strategy	No sample-size calculation was performed.
Data collection	Data are directly obtained from public database listed in the study.
Timing and spatial scale	The data collection period spans from 01/01/2022 to 09/31/2022. The spatial scale of the collected data is mainly at the European city and regional scale.
Data exclusions	No data were excluded.
Reproducibility	The study adopts a four-step approach to predict and assess the contribution of NbS to climate neutrality goals, including systematic meta-analysis, spatial allocation of NbS implementations, emission reduction potential calculation and contribution projection. The study is reproducible at the same or other similar spatial scales when the data types are consistent and sufficient.
Randomization	Not relevant to our study.
Blinding	Not relevant to our study.

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Methods

n/a	Involved in the study
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