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Global urban reforestation can be an important natural climate solution

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Abstract

The climate mitigation potential of urban nature-based solutions (NBSs) is often perceived as insignificant and thus overlooked, as cities primarily pursue NBSs for local ecosystem services. Given the rising interest and capacities in cities for such projects, the potential of urban forests for climate mitigation needs to be better understood. We modelled the global potential and limits of urban reforestation worldwide, and find that 10.9 $\pm$ 2.8 Mha of land (17.6% of all city areas) are suitable for reforestation, which would offset 82.4 $\pm$ 25.7 $MtCO_2e\ yr^{-1}$ of carbon emissions. Among the cities analysed, 1189 are potentially able to offset >25% of their city carbon emissions through reforestation. Urban natural climate solutions should find a place on global and local agendas.

1. Introduction

Nature-based solutions (NBSs), which are actions that harness natural and modified ecosystems to address socio-environmental challenges, are becoming increasingly relevant and important to environmental sustainability efforts [1, 2]. Of the wide range of objectives that NBS may have, those that focus on climate mitigation through carbon sequestration or emissions reduction are commonly dubbed natural climate solutions (NCSs). These NCS can cost-effectively reduce emissions up to a third of the <2 °C target in the Paris Climate Agreement, while delivering a slew of benefits to ecosystem function, biodiversity and local livelihoods [3]. This contribution is increasingly being recognised, as reflected by a threefold increase in NCS investments since 2016 [4]. Solutions typically involve land management actions in rural areas; many target forests, wetlands, grasslands and agricultural lands for protection, management and restoration, located across wide spatial extents [3, 5].

Urban areas consist mostly of impervious surfaces that occupy less than 1%–3% of global land [6, 7], and constantly face a multitude of competing land uses. Their NCS potential is commonly perceived as insignificant and thus frequently overlooked by existing assessments of NCS potential [3, 5, 8]. As such, cities tend to pursue NBS primarily for local ecosystem services such as flood regulation, health benefits, and cultural values [9–11], rather than their ability to contribute toward global climate mitigation.

Cities have high concentrations of human, financial and political resources, and thus have greater capacities to pursue projects that are resource-intensive or require buy-in from numerous stakeholders [12, 13]. Indeed, much of the rising interest in NBS comes from urban centres. Increased recognition of the numerous benefits from urban forests such as cooling, flood protection, pollution mitigation and mental health [9, 10] has accompanied the launch of ambitious tree planting programmes in many cities. Notable examples include Beijing's 50 Million Trees Programme [14], as well as Million Trees Projects in New York [15], Los Angeles [16] and Singapore [17]. However, despite the clear public interest, urban reforestation for climate mitigation has not received the same scientific attention as other reforestation studies (e.g. [8, 18]). Most studies focus on improving local conditions and management [15, 19], but there is a gap in knowledge of the global potential and limits of urban forests for sequestering greenhouse gas emissions. Understanding this can help cities implement NBSs for their climate mitigation benefits as well, and contribute to the development of urban NCS.

To estimate the opportunities and constraints of urban reforestation at a global scale, we first identified unforested green areas within cities [20] covered by grass or shrubs, located within forest, boreal and savannah biomes [21]. Such areas were assumed to be biophysically suitable for reforestation [22]. We excluded all types of land cover that would preclude reforestation, such as impervious surfaces, forests and croplands [21]. To account for land uses that may be considered unsuitable for reforestation [23], we also excluded protected areas, airports, golf courses, sporting grounds, parks and gardens [24]. We then estimated the climate mitigation potential of reforestation within these green areas that could be attributed purely to aboveground biomass growth [8], and compared this potential to the total carbon emissions from each city [25].

2. Methods

2.1. Identifying urban areas

We first extracted city boundaries ($n = 7595$) from high density clusters in the 2015 Global Human Settlement Layer, defined by contiguous grid cells of 1 km^2 (four-connectivity, gap filling) with a density of at least 1500 inhabitants km^{-2} and a minimum population of 50 000 [20]. Our use of the terms 'urban' and 'city' in this study follows this definition.

2.2. Identifying reforestable areas

Within the cities identified, we extracted land cover data from the FROM-GLC10 global land cover product (10 m resolution) for 2017 [21]. Only grass and shrub cover were considered suitable for reforestation; other types of vegetation cover (forest and crop) and non-vegetation land cover types were excluded. Land cover definitions from FROM-GLC10 are as follows [26]: forest comprises broadleaf, needle-leaf and mixed leaf types with canopy cover >15% and height >3 m; grass has herbaceous cover >15%; shrub has woody cover >15% and height between 5 and 0.3 m. Biophysical constraints were introduced by limiting reforestation to areas suitable for forest growth [8]; this included the following biome types: boreal, temperate conifer, temperate broadleaf, subtropical/tropical dry, subtropical/tropical savannah (tree cover exceeding 25%), and subtropical/tropical moist.

2.3. Estimating climate mitigation potential

Within areas suitable for reforestation, we estimated carbon sequestration potential from aboveground carbon using predicted natural forest regrowth values [8] at a spatial resolution of 1 km^2. Finally, we masked out urban land use types that were potentially unsuitable for reforestation using polygons tagged in OpenStreetMap (accessed 1 October 2020) as aerodromes, golf courses, sporting grounds (pitches, tracks and stadiums), parks and gardens [24], similar to [23]. Carbon sequestration potential was compared to city CO_2 emissions from the Emissions Database for Global Atmospheric Research inventory release v5.0 [27]; country regions were adapted from the Maddison definition [28] (see supplementary note 1 for further details (available online at stacks.iop.org/ERL/16/034059/mmedia)).

2.4. Uncertainty

Overall spatial uncertainty from the FROM-GLC10 land cover product was set at ±25.7%, which was the average of the omission (26.4%) and commission (25.0%) errors for the combined grass and shrub land cover type (against other non-grass and non-shrub land cover types) reported in [21]'s confusion matrix. Uncertainty in the projected carbon sequestration value for each pixel was extracted from the raster file provided by the same source [8]. Both uncertainty values were multiplied to derive the total uncertainty for the estimated carbon sequestration potential.

3. Results and discussion

We find that globally there are a total of 10.9 ± 2.8 Mha of urban green areas across 7595 cities that are potentially available for reforestation [20] (table 1). This represents 17.6% of the extent of all city areas, and amounted to a climate mitigation potential of 82.4 ± 25.7 $MtCO_2e$ yr^{-1} (1.1% of total city carbon emissions) (figure 1, table 1), which is equivalent to 5.2% of the maximum biophysical potential of reforestation outside urban areas [8].

Much of this climate mitigation potential is concentrated within countries in the developing Global South (77.7%; 64.06 ± 19.4 $MtCO_2e$ yr^{-1}), given that a large proportion of urban land is located there (67%; 41.5 Mha) (tables 1, S1). This underscores the need for research and practice to be particularly sensitive to the context and challenges faced by cities in the Global South, from governance capacities to socioeconomic needs [29]. For example, cities in the Global South tend to have much higher population densities and are projected to continue growing rapidly [6], exerting additional pressures on urban land. This is reflected in the low proportion of existing urban forest cover within cities in the Global South (6.7%; 2.8 ± 0.7 Mha) compared to the Global North (15.9%; 3.2 ± 0.8), as well as the proportionately smaller extent of green areas available

Table 1. Urban reforestation potential by world regions and city size class, for the year 2015.

		Cities			Existing urban forest		Reforestation potential			
		n	Area (Mha)	2015 emissions $MtCO_2e$	Area (Mha)	%	Area (Mha)	%	Mitigation potential ($MtCO_2e\ yr^{-1}$)	% offset
Region	Global North	1406	20.4	2410	3.24 ± 0.83	15.9	4.06 ± 1.04	19.9	18.33 ± 6.29	0.8
	North America	283	8.66	842	1.67 ± 0.43	19.3	1.49 ± 0.38	17.2	5.74 ± 2.00	0.7
	Western Europe	472	4.86	542	0.86 ± 0.22	17.7	1.24 ± 0.32	25.5	6.78 ± 2.25	1.3
	Eastern Europe	529	3.88	592	0.43 ± 0.11	11.2	0.84 ± 0.22	21.8	2.97 ± 1.06	0.5
	Oceania	28	0.758	59	0.05 ± 0.01	6.9	0.13 ± 0.03	16.7	0.67 ± 0.24	1.1
	Japan (East Asia)	94	2.20	375	0.23 ± 0.06	9.7	0.36 ± 0.09	16.2	2.17 ± 0.74	0.6
	Global South	6189	41.5	4868	2.75 ± 0.71	6.7	6.82 ± 1.75	16.4	64.06 ± 19.36	1.3
	East Asia (minus Japan)	1640	12.07	2945	0.80 ± 0.21	6.6	1.88 ± 0.48	15.5	12.23 ± 3.97	0.4
	Southeast Asia	487	5.75	351	0.43 ± 0.11	7.5	0.64 ± 0.16	11.1	9.63 ± 2.70	2.7
	South Asia	1701	8.15	509	0.64 ± 0.16	7.9	0.92 ± 0.24	11.2	6.62 ± 2.14	1.3
	Middle East	394	2.69	439	0.05 ± 0.01	1.9	0.22 ± 0.06	8.1	0.70 ± 0.27	0.2
	Africa	1189	7.11	272	0.26 ± 0.07	3.7	1.87 ± 0.48	26.3	20.06 ± 5.95	7.4
	Latin America	778	5.73	351	0.58 ± 0.15	10.0	1.30 ± 0.33	22.7	14.82 ± 4.34	4.2
Size class	Small (50–200k)	5023	11.9	555	1.09 ± 0.28	9.1	2.27 ± 0.58	19.0	16.63 ± 5.23	3.0
	Mid (200k-1 m)	2123	18.1	1712	1.67 ± 0.43	9.2	3.22 ± 0.83	17.8	23.51 ± 7.37	1.4
	Large (1–10 m)	419	22.4	2831	2.39 ± 0.61	10.7	4.12 ± 1.06	18.4	32.14 ± 9.93	1.1
	Mega (>10 m)	30	9.5	2178	0.86 ± 0.22	9.0	1.26 ± 0.32	13.2	10.12 ± 3.12	0.5
	Total world	7595	61.87	7277	6.01 ± 1.54	9.7	10.88 ± 2.80	17.6	82.40 ± 25.65	1.1

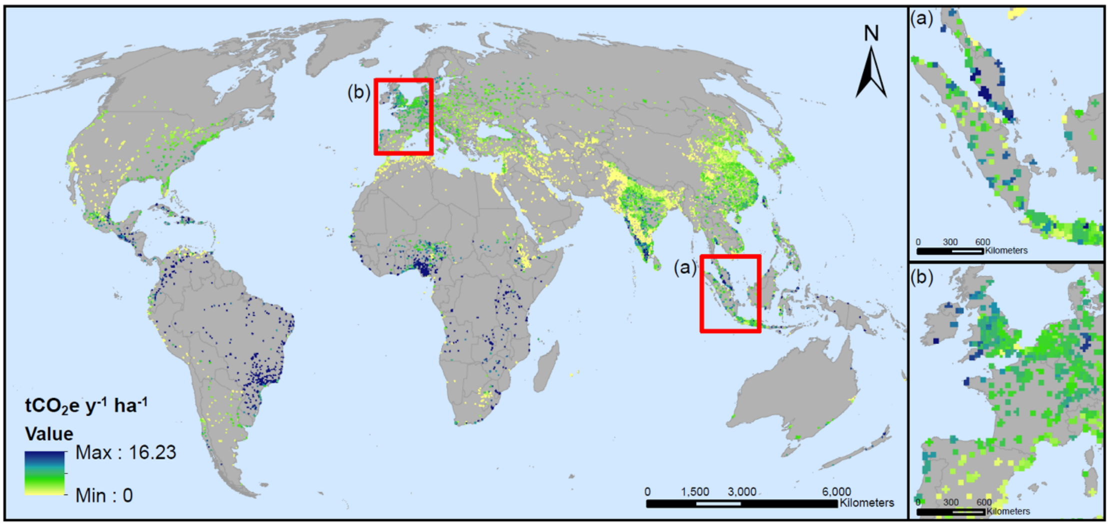

Figure 1. Mean climate mitigation potential ($tCO_2e\ yr^{-1}$) from urban reforestation worldwide. Climate mitigation potential is estimated only for areas that are biophysically suitable for reforestation (grass or shrub cover within forest, boreal and savannah biomes only) within city boundaries. Potentially unsuitable land uses were excluded (e.g. protected areas, airports, golf courses, sporting grounds, parks and gardens). Examples of this potential is shown in panel (a) for parts of Southeast Asia (Global South), and in panel (b) for parts of Western Europe (Global North). The map is resampled by cubic convolution to a spatial resolution of 25 km^2 $pixel^{-1}$ for visibility.

for reforestation in the South (South 16.4%; North 19.9%) (table 1).

Cities from most regions and of all size classes have substantial urban reforestation potential, without any categories being especially dominant (table 1). For example, 30 megacities (population size >10 million) occupy approximately the same land area (9.5 Mha) as 5023 smaller cities (population size 50–200 thousand; total 11.9 Mha) in our analysis, and both have significant shares of the global climate mitigation potential from urban reforestation (megacities 12.3%, 10.1 ± 3.1 $MtCO_2e\ yr^{-1}$; small cities 20.2%, 16.6 ± 5.2 $MtCO_2e\ yr^{-1}$). Since urban governance and characteristics differ greatly between cities, a global agenda to promote urban reforestation must be attuned to their diverse needs.

While the climate mitigation potential of urban reforestation (82.4 ± 25.7 $MtCO_2e\ yr^{-1}$) is much less than conventional reforestation in rural areas shown by other studies (~1600 $MtCO_2e\ yr^{-1}$) [8], our results show that it can contribute substantially to local carbon reduction or mitigation targets [30]. For example, by reforesting green areas within the urban boundaries of Onitsha-Amaigbo, Nigeria, 43% of the area's carbon emissions can theoretically be offset purely through NCS, meeting up to 20% of Nigeria's per capita reduction goals [31] for the area's estimated 5.9 million urban inhabitants (table S1). Overall, we find that for 1189 cities (6.6% of all cities), reforestation of green areas within their boundaries can technically offset more than 25% of local carbon emissions. These were mostly small (n = 977) and mid-sized cities (n = 195) with lower total carbon emissions (table S1), located in Africa (n = 630), South Asia (n = 166) and Latin America (n = 305) (figure 2).

Unlike in non-urban areas, urban forests may face additional biophysical limitations such as poorer soil, light pollution and other anthropogenic disturbances [32, 33], but also potential advantages such as CO_2 fertilisation [34], although these are highly site-specific. To understand whether urban forests generally sequester carbon more slowly than non-urban forests, we extracted 770 points of comparison from the global Forest Carbon database [35] (see supplementary note 1), and found that carbon sequestration rates in urban forests tends to be lower, at 71.9 ± 6.5% (95% CI) of the amount sequestered in non-urban forests. On the other hand, our estimates of climate mitigation potential from urban reforestation assumes a process of natural forest regrowth and succession after initial reforestation [8], and may thus be a conservative estimate since new reforestation projects may utilise more intensive or efficient planting techniques. One popular example is the Miyawaki method, which applies soil restoration and high density multi-stratal planting of late successional species identified from native vegetation, and may increase carbon sequestration by up to five to eight times [36, 37]. In contrast, reforestation through monoculture plantations can also deliver rapid tree growth, but come with risks to the longevity of the carbon stored, such as greater susceptibility to pests and disturbance [38, 39]. Such intensive methods are more feasible for urban than rural areas, and have often been attempted for urban reforestation projects [17, 36, 37]. However, we caution that research on the long-term ecological and successional dynamics of urban forests is still sparse [40].

Figure 2. Percentage of city carbon emissions that can be offset by urban reforestation for each world region. Only biophysically reforestable areas were considered. Unsuitable types of land uses were excluded.

In addition to these possible uncertainties, our estimates of the carbon sequestration potential of urban reforestation through natural aboveground biomass regrowth do not account for the entire life cycle of urban reforestation projects. Urban reforestation projects may replace grass, shrub or street vegetation land covers, which could already be sequestering some carbon. However, existing research suggests that managed urban turfgrass and street vegetation may only sequester small amounts of carbon or be a net emitter, but this is highly variable depending on management practices and site characteristics [41–43]. As such, our methods are likely to not significantly underestimate the carbon sequestration potential. Other carbon fluxes throughout the project life-cycle may also affect the net carbon benefits from urban reforestation, such as the release of carbon through soil respiration by replacing existing land covers during the reforestation process [44], and any management practices carried out. There are also significant indirect benefits, such as from reduced energy consumption for cooling buildings [16, 45]. Further research is much needed on the carbon dynamics—including litter production and belowground soil carbon stocks and fluxes, etc—of existing urban forests which cover 6.0 ± 1.5 Mha (9.7% of city area) worldwide (table 1), on new urban reforestation projects, as well as their associated management practices.

Although NCS have attracted much attention globally, researchers are increasingly advising caution as much of this potential either cannot be realised due to biophysical and socioeconomic constraints [5], or should not be realised due to their potentially damaging effects on ecosystems and livelihoods [18, 46]. For instance, since land is typically scarce in cities, many of the urban areas which we considered to be reforestable could face obstacles from land users and owners as well as future development plans; even legally protected areas may face a high risk of degazettement due to overwhelming financial incentives [47]. Conversely, other cities or districts may face property gluts due to speculation and declining populations [48]. In order to provide a more realistic and conservative estimate of global urban reforestation potential, our study attempts to account for some of these constraints by limiting potential reforestation areas to those within forest, boreal and savannah biomes, and excluding urban areas that may have conflicting land uses. The land uses we selected for exclusion already encompass the major land use types with potential limitations; there will inevitably be exceptions (for example, there may be additional land uses such as cemeteries that are not reforestable, and some areas in parks and gardens which could still be suitable for microforests). Our excluded land uses (amounting to 8.9% of the total biophysically reforestable area in cities) is to provide a better estimate of likely climate mitigation potential and not intended to imply whether they should be reforested, a decision best made locally with full consideration of the benefits, opportunity costs and socioeconomic justice issues. Also, to ensure long-term stakeholder buy-in, urban reforestation must be well-planned in order to reduce potential ecosystem disservices from trees, such as allergenic pollen, release of toxic compounds, damage to people and properties, pests and human–wildlife conflicts [49, 50]. Finally, it is important to note that socioeconomic constraints in rural areas can also be substantial. Prior studies have estimated that after accounting for constraints, rural NCS potential may be as little as 0.3% of its biophysical potential [5]. Some of the factors listed as constraints in rural areas (e.g. livelihoods, prohibitive cost, lack of accessibility) are a lesser problem in cities. Moreover, urban areas are already exhibiting strong interest and capacity for NBSs [14–17], and apart from their direct climate mitigation potential, can also raise awareness and support for rural conservation programmes and rural NCS. As such, urban NCS should also find a place on global and local NCS agendas.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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