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Urban boundaries are an underexplored frontier for ecological restoration

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The restoration of degraded ecosystems is crucial for addressing climate, biodiversity, and health challenges. The benefits of these restorations are amplified when implemented closer to urban populations, particularly for climate adaptation and human health. This study investigated the potential of urban areas for forest restoration, introducing a novel distinction between dense urban areas and urban boundaries (peripheral zones of urban centers), and comparing their dynamics to rural areas. We analyzed three decades of deforestation and regeneration dynamics in Brazil, quantifying and mapping land-use transitions to assess restoration potential. Results show that forest transition has already occurred across all the different types of areas considered. Urban boundaries exhibited highly dynamic land use and high regeneration rates despite limited policy support. The landscape dynamics and the presence of environmentally risky areas reveal that urban boundaries contain significant areas that hold potential for restoration, which could significantly contribute to achieving national or subnational restoration targets. Integrating restoration into urban boundary planning offers both ecological and social benefits to a substantial portion of the population. Our findings reveal a missed opportunity to extend restoration efforts beyond the traditionally targeted rural areas, positioning urban boundaries as key areas for innovative land-use strategies and restoration initiatives.

Keywords Urban forest restoration, Nature-based solution, Climate change adaptation, Urban ecosystem services.

To tackle the challenges posed by climate change, resource insecurity, biodiversity loss, and health emergencies, it is essential to protect and sustainably manage natural landscapes as well as to restore degraded ecosystems[1,2]. If well-planned and managed, ecological restoration has the potential to address climate, biodiversity and social issues[3–5]. The effectiveness of ecological restoration relies on careful consideration of its motivation, location, and the implementation strategies[6]. Most restoration targets, whether global, like the Bonn Challenge target of restoring 350 million hectares worldwide by 2030[7], or Brazil's goal to restore 12 million hectares[5]are primarily focused on rural areas due to the availability of land and lower costs. However, if restoration efforts aim to impact climate change adaptation, not only mitigation, it is crucial to bring these actions closer to urban areas, either to the dense urban core or to the urban boundaries[8,9] - peripheral areas around urban centers. Thus, the main objective of this study is to investigate the potential of urban areas, particularly urban boundaries, for forest restoration. As areas highly vulnerable to climate change and extreme weather events[10]cities represent territories where interventions can potentially benefit millions of people. Urban areas are home to 55% of the global population. By 2050, an estimated 2.4 billion additional people will reside in cities, reflecting an urbanization rate comparable to creating a city the size of London every seven weeks, urbanizing approximately 120 million ha—an area larger than the entire territory of Colombia[11,12].

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The proximity of forests and trees to urban areas provides a diverse and well-documented array of benefits to residents, including improvements to mental and physical health, recreation and aesthetics[13–16]. Such green infrastructure also contributes to local climate regulation, mitigation of extreme weather events, air purification, water regulation and purification, food and fuelwood provision, waste treatment, and runoff mitigation - often through interconnected processes[16,17]. The benefits to residents are positively affected by the quantity and proximity of green spaces, particularly in a land-sharing configuration (i.e. dispersed green spaces across urban areas)[14]and may vary based on individual and locational characteristics[13]. Although potential health risks, such as pollutant entrapment under the tree canopy, or an increase in allergies (e.g. pollen), should be considered, they do not outweigh the overall benefits of forest proximity[8].

Despite the essential role of green and forested areas in promoting health and enhancing climate resilience in cities, urbanization generally impinges on these spaces. For example, between 1992 and 2000, urban expansion was responsible for the loss of 19 million hectares of natural habitat globally, representing 16% of the total natural habitat loss during this period[11]. From 1992 to 2015, global urban expansion directly eliminated 3.3 million hectares of forest. Additionally, 17.8 to 32.4 million hectares of forest were indirectly lost due to cropland displacement[18]. Globally, urban tree cover significantly declined between 2012 and 2017, with an annual loss of about 40,000 hectares affecting all continents except Europe[19]. By 2030, urban growth is projected to have tripled the extent of urban land since the year 2000, endangering 29 million hectares of natural habitat and significantly threatening biodiversity hotspots such as the Atlantic Forest[11,20]. The United States, Brazil, Nigeria and China are projected to lose the most natural habitat due to urban growth— exceeding 1 million hectares[11]. Previous studies have demonstrated that cities experiencing rapid urbanization are more prone to vegetation degradation[21] and the majority of urban centers display lower vegetation cover when compared to their surrounding areas[22]. These outcomes are also contingent on the period of analysis, as the reduction in vegetation is more marked during phases of urban expansion, while green spaces may increase during phases of urban consolidation[21].

While studies have emphasized the impacts of urban expansion on natural areas[11,18,19] and raised concerns about projected urban growth and the associated loss of natural habitats[11,20]it is worth noting that, between 2000 and 2018, 70% of the 1,688 urban agglomerations larger than 100 km² worldwide experienced an increase in vegetation. These positive trends were predominantly seen in cities across Europe and North America, while cities in Africa, South America, and Asia continue to show declines[23]. This shift from net deforestation to net reforestation, known as Forest Transition, has complex socio-economic characteristics[24,25]. In the context of urban areas and their surroundings, forest plantations, the natural regeneration of formerly agricultural lands and pastures, incentives for the implementation of green infrastructure and GDP per capita are likely to constitute relevant drivers of vegetation recovery[23,26]. Positive trends in higher latitudes have also been associated with longer growing seasons due to global warming and the urban heat island effect[23].

However, although these trends appear to be more common in the Global North, they are not consistently observed in the Global South[21,23,26]. This process requires further investigation, as does the identification of areas suitable for restoration in urbanized regions, where particular complexities exist and strategies must be tailored to local conditions[27]. These strategies should consider not only ecological dimensions but also social, historical, and cultural factors, which may differ significantly between urban and rural settings[28–30]. In this regard, to maximize the benefits of restoration initiatives, researchers recommend prioritizing areas that are accessible to the population and that currently have limited green space, thereby aligning the supply of ecosystem services with existing demand[29,31]. In this context, urban boundaries or peri-urban zones have been identified as potentially suitable for ecological restoration[23]. These areas feature diverse land uses—such as residential neighborhoods, agricultural lands, recreational spaces, urban infrastructure and water zones—that interact closely with urban activities (note S1).

Previous studies on forest regeneration in peri-urban areas have evaluated patterns of forest regeneration, revealing that forest expansion growth often occurs near urban areas and that regenerated areas may exhibit greater species diversity, partly due to the presence of exotic species[32]. The potential for new forests in peri-urban contexts has also been analyzed under different restoration effort scenarios: considering all non-forested land as available for restoration; excluding areas where the potential natural vegetation would not be forest; and excluding areas projected to become unsuitable for forests in the future due to climate change[9]. Although not specific to peri-urban areas, other studies have adopted similar approaches to define potential areas for restoration, evaluating historical land-use change and considering as potential those areas converted from natural ecosystems or those with degraded environmental quality, as well as future land demand and urban expansion scenarios[29]. Recommendations for selecting suitable areas include avoiding areas that were not originally forested, prioritizing sites near existing forest fragments, and assessing both current land uses and potential land-use displacement to avoid triggering new deforestation[4]. It is worth noting that previous studies often did not clearly distinguish between dense urban and peri-urban areas which is considered a key aspect in designing effective and context-sensitive restoration public policies[27,33].

In this study we investigated the potential of urban areas for forest restoration in the most populated region of Brazil, the State of São Paulo, where the largest megalopolis in the southern hemisphere is located: the São Paulo macro-metropolis, home to 32.7 million people. The novel contribution we bring to the literature lies in distinguishing between dense urban areas and urban boundaries, analyzing them separately, and comparing their dynamics to those of rural areas (table S1). We analyzed deforestation-regeneration dynamics over 30 years and compared dense urban areas, urban boundaries, and rural areas to quantify and spatialize land dynamics, accessing the potential of both urban areas to promote restoration. Over 90% of vegetation losses involved forest physiognomies[34]. For this reason, we use the term "deforestation" instead of "native vegetation loss" to emphasize the predominance of deforestation in these dynamics and the critical need for forest restoration efforts. We also identified focal areas for urban restoration, selecting them based on current dynamics, potential benefits, and feasibility within the existing legal framework.

Our findings indicate that forest transition has already occurred across São Paulo State, although urban areas - particularly dense urban regions - have experienced this process more recently. Urban boundaries have emerged as the most dynamic regions, showing the highest rates of regeneration. Beyond these regenerated areas, urban boundaries hold an estimated 410 thousand hectares (about half of the State's urban boundaries) potentially available for restoration across São Paulo State, including 235 thousand hectares in the macro-metropolis. We highlight urban boundaries as a promising frontier for expanding restoration efforts near densely populated areas, providing benefits for public health and climate resilience. We also discuss implications for public policy and propose directions for future action.

Results

Forest transition has already occurred through a series of transitions taking place successively across the studied contexts

Results indicate that forest transition has occurred across the entire study area, first in rural regions, then expanding to urban boundaries, and most recently to dense urban areas (Fig. 1 State and Fig. 2 macro-metropolis). The transition in each context showed a recurring trend of increasing regeneration and decreasing deforestation rates, with the higher rates taking place in dense urban areas as a consequence of very small initial percentages of natural cover in these areas. For both the State and the macro-metropolis, natural cover loss was concentrated until the early 2000s. Since then, there has been an annual increase in natural cover, sufficient to surpass the cover in the reference year (1989) in urban boundaries and rural areas, but not in dense urban areas (Fig. S1). In urban boundaries and dense urban areas, urban land use has primarily expanded at the expense of pasture and agricultural-pasture mosaics. In contrast, forest land use predominates in the rural areas of the macro-metropolis.

While the total regenerated area in dense urban regions is small, it shows a slightly positive trend. In urban boundaries, the percentage of regenerated areas is similar to that of rural regions. Urban boundaries exhibit an increasing regeneration trend, whereas rural areas remain stable at the state level and show a declining trend within the macro-metropolis (Figs. S2 and S3).

Urban boundaries are the most dynamic area since forest transition

Most areas in the State of São Paulo and the macro-metropolis have shown little change after the inflection point for forest transition (around 2005), largely retaining their 2005 conditions through to 2020 (Figs. 3, S4 and S5). Only 8.3% of the State and 9.1% of the macro-metropolis experienced change. Change rates appear to be higher in urban boundaries than in rural areas. The urban boundaries of the macro-metropolis exhibit greater dynamism compared to those of the State. Within these boundaries lie focal areas, defined as regions encompassing risk zones—such as those prone to flooding, landslides, erosion, and riverbank collapse —as well as areas of permanent preservation (APPs) associated with rivers and streams. These focal areas demonstrate even higher rates of change. In contrast, dense urban areas are the most stable, exhibiting the lowest rates of change. (Figs. 4—State and 5—Macro-Metropolis and Tables S2 and S3).

Among the changes observed in both rural areas and urban boundaries of the State and the macro-metropolis, regeneration exceeds deforestation. The highest regeneration rate was found in focal areas, followed by the State's urban boundaries and the macro-metropolis' urban boundaries. In dense urban areas of the macro-metropolis, deforestation trajectories are more prevalent, while in the State's dense urban areas, regeneration slightly surpasses deforestation (Fig. 4- State and 5—Macro-Metropolis and Table S2 and S3).

Landscape connectivity has not increased despite regeneration

Regeneration from 2005 to 2020 increased the total forest area across all regions analyzed. However, this gain came with a notable rise in fragmentation (especially in the number of patches) in the scenario that included both deforestation and regeneration, compared to the 2005 baseline and the "2020 without regeneration" scenario (Table S4). Thus, regeneration has not increased connectivity or the size of the largest fragment, indicating that regeneration primarily occurred in isolated patches, which did not substantially enhance landscape connectivity, despite a small increase in mean patch size.

Approximately 50% of the state's urban boundaries may be suitable for restoration

Urban areas (dense urban and urban boundaries) in the State of São Paulo have between 481,279 and 556,317 hectares (33.5% −38.7%) potentially available for restoration, with half of this area located in the macro-metropolis (Table 1). Approximately 51–60% of the State's urban boundaries may be suitable for restoration, compared to only about 10% of dense urban areas. In restoration focal areas, where restoration is already legally mandated, there are between 39,890 and 44,122 hectares (48.4%-53.5%) without natural cover, requiring restoration. Urban boundaries have 6 to 7 times more area potentially available for restoration compared to dense urban areas.

Discussion

We showed that although urban boundaries account for less than 4% of São Paulo State and are under pressure from urban expansion, they hold significant potential for increasing natural cover. These dynamic regions have seen more regeneration than deforestation since 2005, even with the scarcity of targeted public policies directly promoting natural cover increase in such a context. They still contain 413,539 hectares (50.9%) potentially suitable for restoration— which represents about one-third of the state's restoration target of 1.5 million hectares by 2050[35]. Of this total, 39,890 hectares fall within areas legally protected (APP) and were likely subject to illegal deforestation, requiring urgent restoration. Although the regeneration that has taken place over the past 15 years

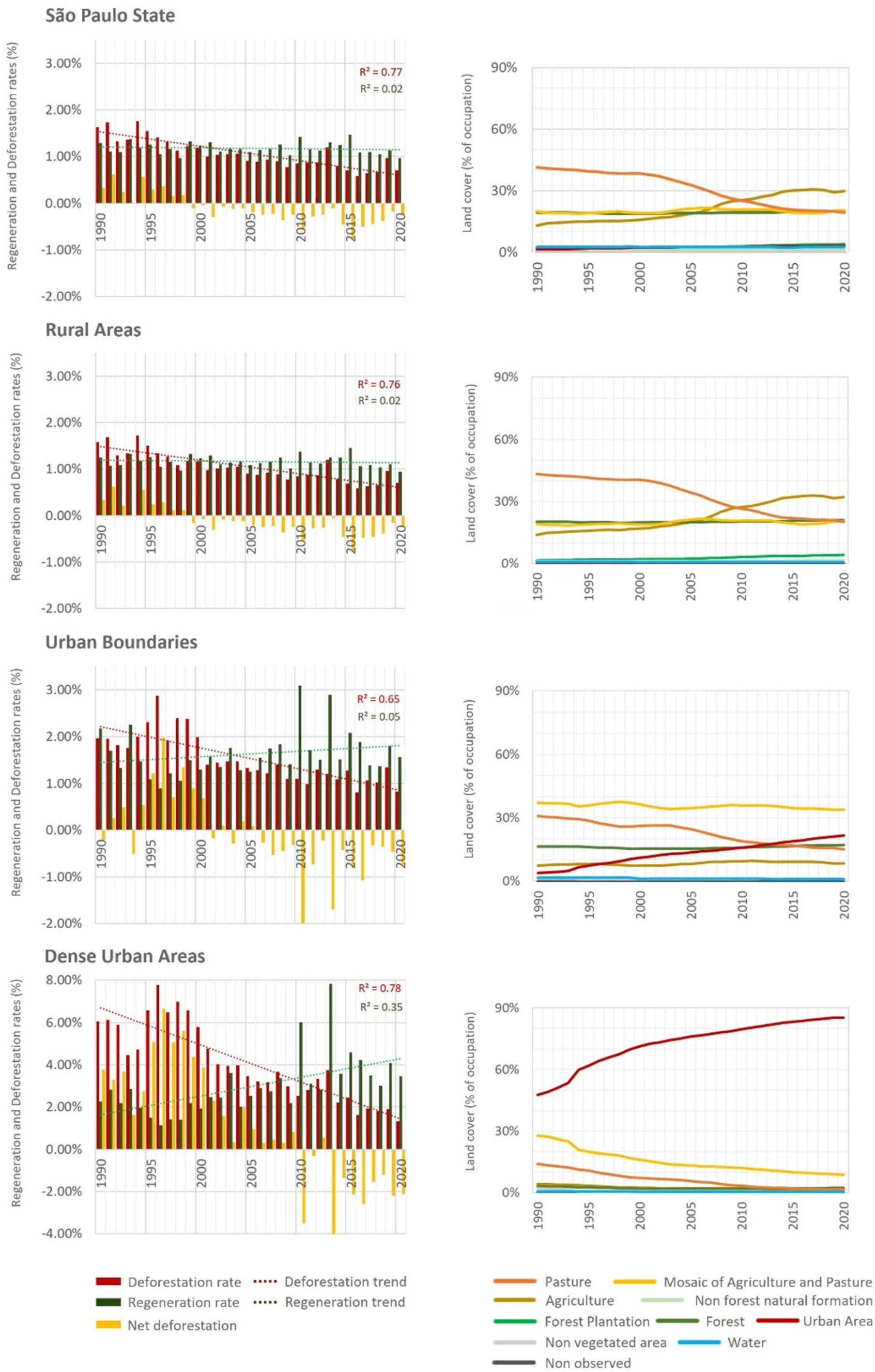


Fig. 1. Regeneration and deforestation rates and trends in the entire São Paulo State, in rural areas, in urban boundaries and in dense urban areas from 1990 and 2020, compared with land cover in the same period. Note: y-axis scale in the "Dense Urban Areas" differs from other panels along the first column.

follows a more fragmented pattern and does not necessarily enhance connectivity for biodiversity, it may still contribute to local climate regulation, water flow regulation and provisioning, air quality improvement, extreme event prevention, and recreational services, as suggested by previous studies. All those benefits are essential for the well-being of the urban population and for addressing climate change at the local, regional and global scales.

The observed decrease in deforestation rates and the concurrent increase in regeneration rates across the study areas demonstrate a forest transition, consistent with findings reported in previous studies[24,36]. Forest transition has complex socio-economic characteristics[24,25] related to the mechanization of agriculture, the emergence of multifunctional landscapes in rural areas and land abandonment[25,38]. This observed forest transition may have

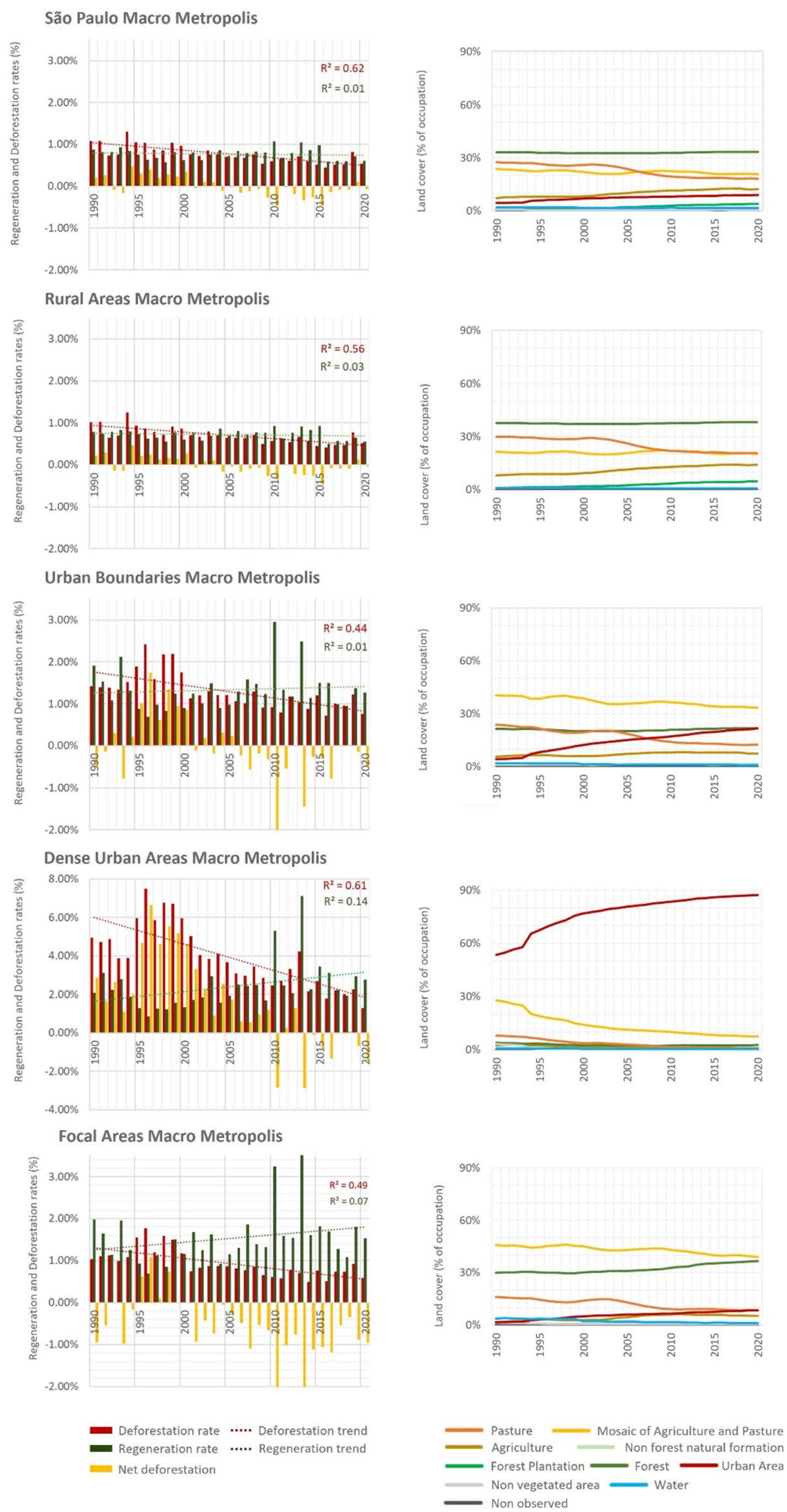


Fig. 2. Regeneration and deforestation rates and trends in the entire São Paulo macro-metropolis, in rural areas, in urban boundaries, in dense urban areas and in restoration focal areas from 1990 and 2020, compared with land cover in the same period. Note: y-axis scale in the "Dense Urban Areas" differs from other panels along the first column.

been influenced by state policies designed to promote forest cover increase. For instance, the Intergovernmental Fiscal Transfer for Conservation (the *ICMS Ecológico*) stimulates the creation of Protected Areas, and has been operating in the São Paulo state since 1995[39,40]. Also, the Atlantic Forest Law (Law 11.428/2006), approved in 2006, has increased legal protection for forest remnants in this threatened biome[41]. But forest transitions in

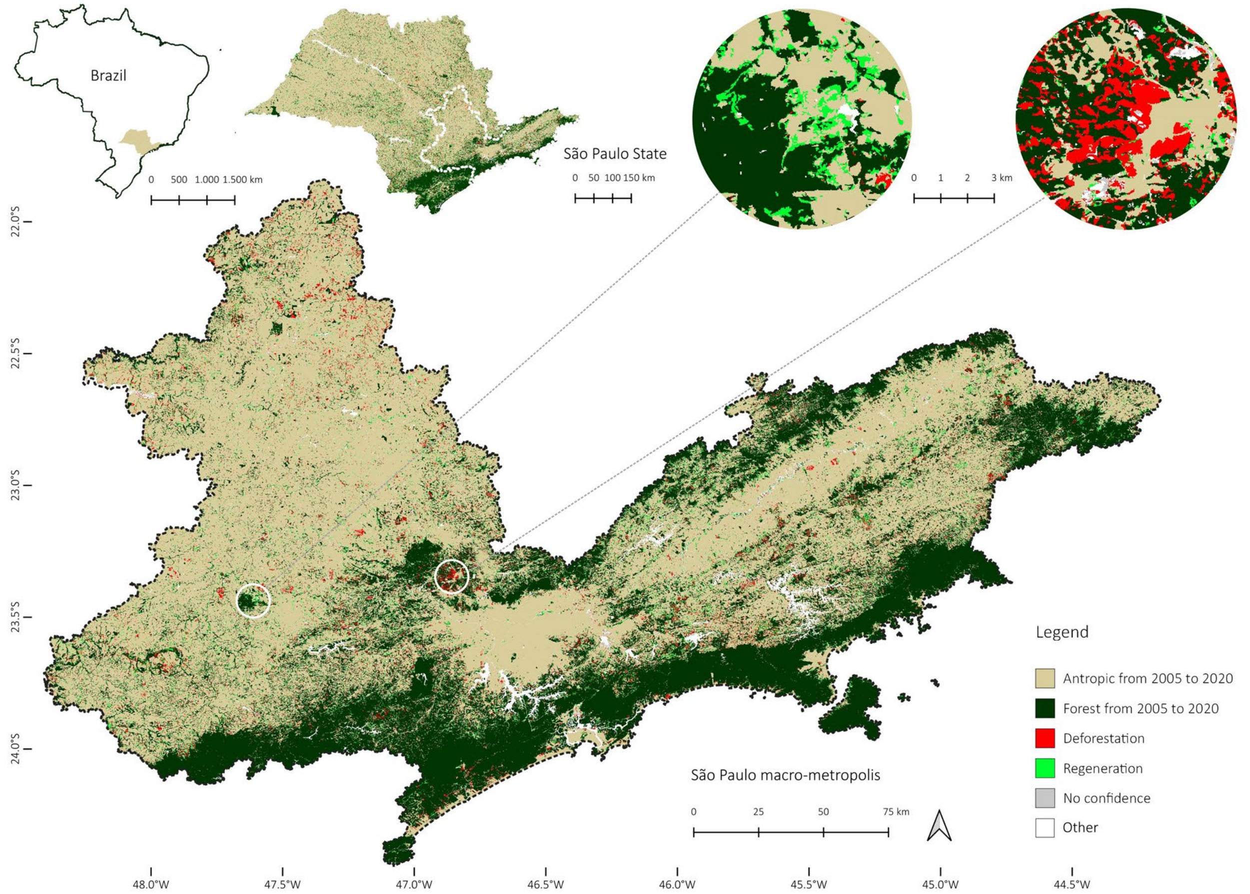


Fig. 3. Trajectories from 2005 to 2020 showing four classes analyzed in the São Paulo State and the macro-metropolis. Source: The maps were created using QGIS software version 3.28.3 (https://qgis.org/). The map showing the 7 analyzed classes, corresponding to Figs. 4 and 5, is available in the Supplementary Material, Figure S5.

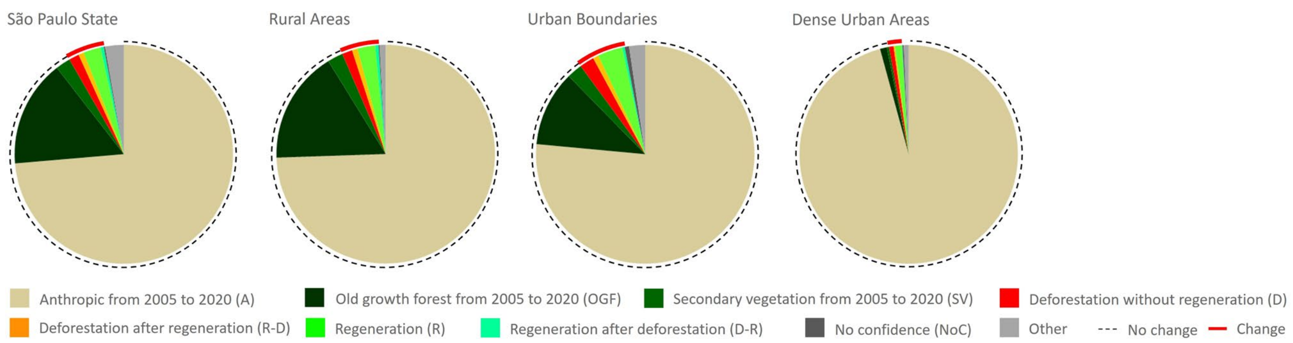


Fig. 4. Trajectories from 2005 to 2020 for rural areas, urban boundaries and dense urban areas of the State of São Paulo, highlighting in outer red line classes that represent changes from 2005 to 2020.

dense urban areas and urban boundaries are not widely discussed as data is commonly reported in the municipal level or for the entire biome[25,36,37].

Although all areas showed a reduction in deforestation rates and in the proportion of deforested areas relative to the total area of each class, regeneration displayed a different pattern. In dense urban areas, despite higher regeneration rates, and the small percentages of forest cover at the initial point of the analysis, the gains have not been sufficient to restore natural cover to 1989 levels. The small proportion of regenerated land in dense urban areas may be due to built densification in the studied period, which could limit available land for regeneration, concentrating the natural cover increase in high-income areas and hindering similar gains in highly dense and

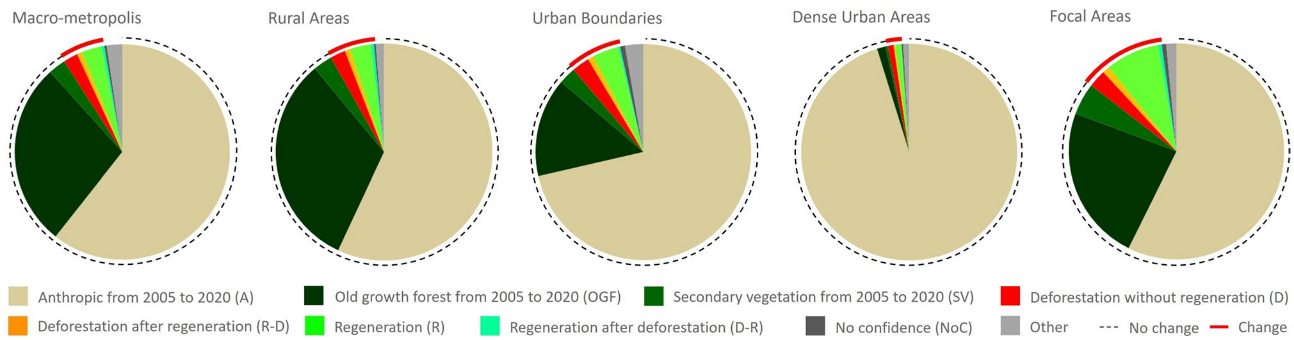


Fig. 5. Trajectories from 2005 to 2020 for rural areas, urban boundaries, dense urban areas and focal restoration areas of the São Paulo macro-metropolis, highlighting outer red line classes that represent changes from 2005 to 2020.

Area	Total Area (ha)	Restoration Potential Areas (including agricultural areas in 2020) ha and % in relation to total class area		Restoration Potential Areas (excluding agricultural areas in 2020) ha and % in relation to total class area	
State					
Urban boundaries	811,717	482,331	59.4%	413,539	50.9%
Dense urban areas	624,868	73,986	11.8%	68,190	10.9%
Total	*1,436,585*	*556,317*	*38.7%*	*481,279*	*33.5%*
Macro-metropolis					
Urban boundaries	492,959	272,393	55.3%	235,063	47.7%
Dense urban areas	373,726	36,542	9.8%	33,233	8.9%
Total	*866,685*	*308,935*	*35.6%*	*268,296*	*30.9%*
Restoration focal areas	82,388	44,122	53.5%	39,890	48.4%

Table 1. Restoration potential areas identified based on previous land cover trajectories, with and without the inclusion of agricultural areas.

lower-income neighborhoods[42,43]. On the other hand, in urban boundaries, the proportion of regenerated area is larger, similar to those in rural areas, and current natural cover exceeds that of 1989, despite urban expansion. The most dynamic areas of the State, the urban boundaries, are showing positive trends in regeneration, with a steady increase in the proportion of regenerated areas. This increase in regeneration may be associated with land abandonment, allowing for natural regeneration, or with the potential rise of medium- and high-income residential developments that, in compliance with legal requirements, restore previously deforested areas. A better understanding of the social and economic drivers and consequences of this transition process will allow us to develop new interventions specifically designed to stimulate forest regeneration on urban boundaries, close to where most of the world's population currently lives and will live in the future. This is certainly a restoration and land use policy gap to be addressed.

Previous studies have documented forest expansion surrounding densely populated urban areas in regions such as Mediterranean Europe[44]Northern Argentina[32], [45]and Northern China[46]whereas a decline in forest cover has been observed in Southern China[46]where accelerated urban growth aligns with a broader trend of vegetation loss in rapidly urbanizing cities[21]. Methodological variations across studies, along with differing definitions of urban areas and boundaries, present challenges to direct comparison and limit the generalizability of findings across contexts. However, these differences underscore the importance of segmented analyses in densely urbanized areas and urban boundaries, as trends may diverge, thus providing more targeted insights for public policy planning.

The State of São Paulo has set a restoration goal of 1.5 million hectares. Considering current legislation, there are areas that must be restored (the focal areas in this study) and areas where restoration may take place. It will certainly be easier to meet these restoration goals in areas with lower opportunity costs. However, the benefits associated with such restoration – including benefits related to water provision[47]microclimate regulation[48]air quality regulation[49] and climate-related hazard[3]—would be amplified through proximity to densely populated urban areas. The value of these enhanced benefits should be accounted for. This is especially crucial in a scenario of extreme events, which have significant impacts on urban populations[10,50,51].

Urban boundaries encompass a diversity of actors, land use histories, environmental and socio-economic conditions. Consequently, restoration efforts in these areas may include natural regeneration and ecological restoration aimed at recovering native vegetation and ecosystem services; productive restoration models that integrate restoration with the cultivation of native or naturalized species for timber and non-timber forest products, thereby contributing to food security and income generation for local landholders; and, in some cases, objectives related to urban green infrastructure. This multifunctional perspective will be essential for guiding land prioritization, as it enables restoration strategies to be tailored not only to the biophysical suitability of the land but also to the interests, capacities, and constraints of local stakeholders.

Considering all areas lacking natural cover in the state's urban boundaries, which will also require a specific suitability analysis, we could potentially meet 27–32% of the state restoration goal within these areas. We acknowledge that urban boundaries are often prime land for urban expansion, and other uses, such as agriculture — particularly on small family farms — are especially valuable in these areas. As a result, restoration efforts may have to be negotiated and may coexist with other uses. Furthermore, such forest restoration efforts in urban boundaries must mitigate the risk of displacing vulnerable populations to more distant areas, as well as the potential gentrification that could accompany environmental improvements in these regions[52,53]. On the other hand, the potential benefits to urban populations make it worthwhile to address the complexities of better integrating and promoting restoration around cities. Additionally, new forms of restoration compatibility may be possible through agroforestry systems and urban designs that emphasize dense and connected forest areas[54]. These approaches undoubtedly require specific planning and incentives, in addition to the restoration of focal areas along rivers and streams and, particularly, in risk areas.

Considering that the success of restoration efforts can be favored by proximity to well-conserved areas[55,56]the urban boundaries of the São Paulo macro-metropolis present an opportunity for targeted projects, as they are adjacent to the most well-preserved areas in the State and neighbor to more than 30 million people. Furthermore, the proximity to well-conserved areas can facilitate natural regeneration without the need for active planting, which can reduce restoration costs[57]. On the other hand, when restoration requires more labor intensity, proximity to human populations, and thus the labor pool, can be considered an advantage, taking into account the huge potential that ecosystem restoration offers for job creation[58].

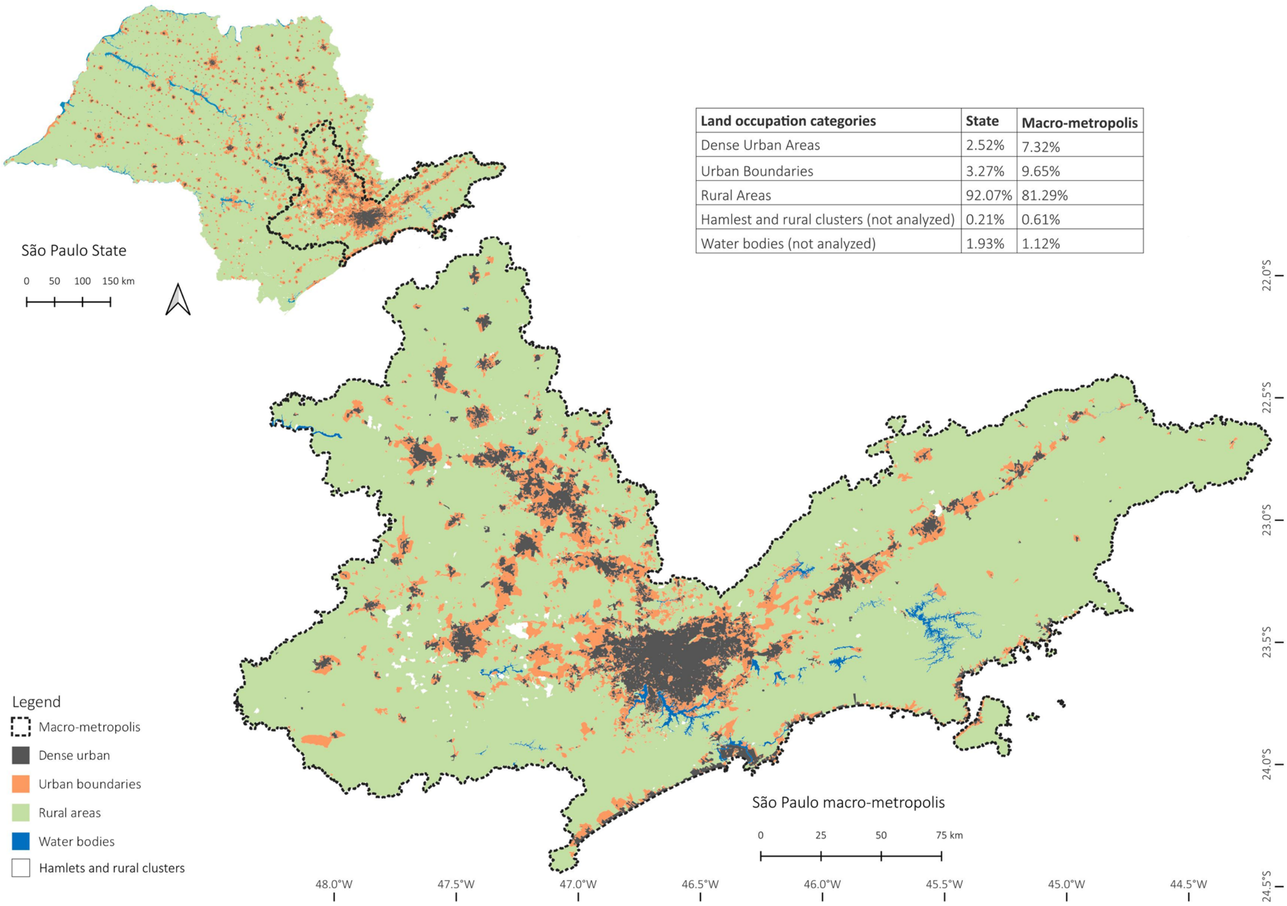
Given the scarcity of specific instruments or programs designed to stimulate restoration in urban boundaries, and the significant potential of these areas to bring restoration efforts closer to where the majority of the population resides, it is essential to leverage this opportunity through targeted public policies. To address this, we highlight several key initiatives:

(i) Protecting and restoring at-risk areas, which is crucial given the increasing intensity, frequency, and duration of extreme events[59].
(ii) Promoting the creation of ecological corridors in areas undergoing urban expansion, especially in condominiums and allotments, prioritizing APPs, which offer protection for rivers and streams and also have the potential to connect dense urban, urban boundaries and rural areas[27]. The corridors can be done through different strategies, in private or public areas and can be aligned with recreation activities in Linear Parks[60].
(iii) Investing in the protection of large forest patches surrounding urban areas, essential for water management[61,62] and recreation. This can be encouraged through policies that establish new nature reserves or through the expropriation of natural areas using environmental compensation funds.
(iv) Encouraging initiatives that align environmental conservation and food security, such as agroforestry systems, conservation agriculture or food systems that directly benefit from ecosystem services and therefore promote conservation[63].
(v) Ensuring climate and environmental justice for vulnerable populations located on urban boundaries, ensuring that the incentives promoted and the actions implemented do not produce gentrification[64,65].

We acknowledge the complexity of urban boundaries, particularly the various interests involved in these areas. However, our study highlights an underexplored opportunity to consider the additional benefits that this restoration could provide, introducing a new target territory to the complex discussion on forest restoration and a new land use within the intricate territorial dynamics of urban boundaries.

Methods

The study was conducted across the state of São Paulo, Brazil's most populous region. A vast area of approximately 24.8 million hectares, with 645 municipalities and 44,4 million inhabitants[66]. São Paulo state features diverse environmental conditions, including coastal zones, mountainous terrain, and interior plateaus. The state also encompasses two major biomes: the Atlantic Forest and the Cerrado (Brazilian Savanna), both considered global biodiversity hotspots[67]. Given its unique characteristics, we also conducted a separate analysis focusing on the São Paulo macro-metropolis (Fig.S6), the largest and most populous region in the Southern Hemisphere. This region covers an area of approximately 5.1 million hectares and is home to 32,7 million people[66]. The two study areas (São Paulo State and São Paulo macro-metropolis) were initially characterized according to the land occupation categories considering dense urban areas, urban boundaries and rural areas (Fig. 6 and Table S5). Urban boundaries refer to areas on the periphery of urban centers, irrespective of their size. Commonly termed peri-urban areas, urban edge, urban fringe, or the urban-rural interface (table S1), these zones lack a universally accepted definition[33] and are characterized by diverse land uses, from residential neighborhoods to agricultural lands. Around densely urbanized regions, these uses interact dynamically with urban activities, including high- and low-income housing complexes or condominiums, small-scale agriculture, recreational and leisure spaces, and water resource zones. In this study, we classified land occupation categories based on the Brazilian Institute of Geography and Statistics (IBGE) definitions and limits from 2021. Areas with high building density



Land occupation categories	State	Macro-metropolis
Dense Urban Areas	2.52%	7.32%
Urban Boundaries	3.27%	9.65%
Rural Areas	92.07%	81.29%
Hamlest and rural clusters (not analyzed)	0.21%	0.61%
Water bodies (not analyzed)	1.93%	1.12%

Fig. 6. São Paulo State and São Paulo macro-metropolis dense urban areas, urban boundaries and rural areas. Water bodies and other types of occupation were not analyzed (For class description, please refer to Table S5). Source: The maps were created using QGIS software version 3.28.3 (https://qgis.org/).

were designated as dense urban areas, while urban boundaries referred to urban zones with lower building density, encompassing rural clusters with urban extensions. Rural areas, in turn, were characterized by dispersed households and the typical presence of agricultural establishments (Table S5 and Note S1). The assessment used by IBGE to differentiate areas of high and low building density, as well as rural areas, is based on the visual interpretation of high-resolution satellite imagery and is validated through field verification by IBGE technical teams.

Deforestation-regeneration

We analyzed the deforestation-regeneration dynamics from 1990 to 2020 using data from the eighth collection of MapBiomas, an initiative that produces annual land use and land cover mapping based on random forest applied to Landsat archives using Google EarthEngine[68]. MapBiomas considers deforestation as the transition between natural land cover (forested and non-forested – e.g. wetland, grassland) and anthropic land uses (e.g. urban areas, agriculture, forest plantation) and regeneration as the transition between anthropic land uses to natural land cover (Table S6). We compared deforestation and regeneration rates, as well as the evolution of land use and land cover in urban areas, urban boundaries, and rural areas of the state and the macro-metropolis, identifying quantitative differences between the areas. The inflection point marking the forest transition was defined as the first year in which regeneration exceeded deforestation, with this pattern sustained in the subsequent years; it corresponds to the intersection of the trend lines shown in Figs. 1 and 2.

Land cover trajectories

We also mapped land cover trajectories in urban areas following the forest transition at the pixel scale (2005–2020). We selected 2005 as the starting year for the trajectory analysis because it is the first year after the forest transition in the macro-metropolis (after 2004, regeneration rates consistently surpassed deforestation rates). This analysis considered the final land cover classes of each pixel, as well as their intermediate changes, defining seven trajectory classes (Table 2 and Fig.S7).

Class name	Class description	Group
1. Anthropic- from 2005 to 2020 (A)	Pixel classified as anthropic in all scenes.	No change between 2005–2020
2. Old growth forest- from 2005 to 2020 (1 V)	Pixel classified as old growth vegetation in all scenes.	
3. Secondary vegetation-from 2005 to 2020 (2 V)	Pixel classified as secondary vegetation in all scenes.	
4. Deforestation without regeneration (D)	Pixel classified as deforestation in any year without any occurrence of regeneration.	Deforestation without regeneration
5. Deforestation after regeneration (R-D)	Pixel classified as anthropic in 2020 with occurrence of regeneration and deforestation between 2005 and 2020.	
6. Regeneration (R)	Pixel classified as regeneration in any year between 2005–2020, without any occurrence of deforestation, and classified as natural land cover in 2020.	Regeneration
7. Regeneration after deforestation (D-R)	Pixel classified as natural land cover in 2020 with occurrence of regeneration and deforestation between 2005 and 2020.	
8. No confidence (NoC)	Transitions that need more information to be confirmed (please refer to SM).	No confidence

Table 2. Main trajectories of change observed from 2005–2020.

Fragmentation and connectivity

Based on the trajectories of deforestation and regeneration, we assessed whether the regeneration following the forest transition contributed to reducing landscape fragmentation, comparing the native vegetation structure in 2020 with and without regeneration. Specifically, we analyzed landscape structure using metrics of connectivity and fragmentation (number of patches, largest patch index, mean patch area and its standard deviation).

Identifying restoration potential areas

To identify potential urban areas for forest restoration, we used the land cover trajectories to identify the land-use types that most frequently precede natural regeneration. Specifically, for each pixel that underwent regeneration, we determined the year of regeneration and extracted the most recent anthropic land-use class preceding that event. This analysis allowed us to identify which land-use types historically transition to natural vegetation (Table S7). We then considered two scenarios differing in whether agricultural lands were included as restoration candidates. Agricultural areas, due to their higher opportunity costs, may be more challenging to allocate for forest restoration[69]. Natural formations, both forest and non-forest, were not considered as potential areas, as well as beach, dunes and sand spots, water and urban areas. After defining the potential areas for forest restoration, we selected focal areas among them, including the risk areas defined by the State Geological Institute (flooding, landslides, erosion, and riverbank collapse)[70] and areas of permanent preservation (APP) of rivers and streams in the urban boundaries of the macro-metropolis. Under the Federal Law 12.651/2012 (Forest Code)[71]APPs are based on river width length. Since this data is not available for all rivers, we used the minimum APP (30 m) as a reference. Risk areas and riparian APP were merged to define the *restoration focal areas*, designated as such due to legal mandates, unsuitability for development, and their location in the study region.

Data availability

The map data generated by this research are available in the Mendeley Data repository [DOI:10.17632/4cngm8b-v5h.1 and 10.17632/jz9bxwwzdk.1]. This paper does not report original code. Any additional information required to reanalyze the data reported in this paper is available from the corresponding author upon request.

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Author contributions

Conceptualization, JPM and LSF.; methodology, LSF, JPM, ALC, NN.; investigation, LSF, ALC.; writing—original draft, LSF; writing—review & editing, LSF, GdG, RBC, ALC, DHD, NN, PR, LSS, RV and JPM.; funding acquisition, JPM. All authors have read and agreed to this version of the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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