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Addressing the sustainable urbanism paradox: tipping points for the operational reconciliation of dense and green morphologies

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To improve biodiversity and human living conditions in the Anthropocene, urban forms must reconcile density with vegetation to meet the dual sustainability-liveability challenge. This paradox poses a dilemma for urban planners and is a critical research issue requiring comprehensive analyses. Multi-family residential housing holds the potential to achieve balanced density-greening, proximity ecosystem services and human-nature connectedness, but meeting such objectives relies on finding balanced morphologies and metrics at an operational scale. Analysing 11,593 plots in the Lyon metropolitan area (France) using a systemic approach, we identified critical tipping points in morphology and greening. Density explained only 6% of Plot Greening, while morphology and landscaping accounted for 94%. We identified an open-space ratio (unbuilt area/floor area) >0.3 as a morphological threshold to achieve sustainable green supply. Operational morphologies balancing density and greening were modelled and illustrated across building heights, providing guidelines for emerging regulatory tools in sustainable urban planning.

Global urbanisation is a prominent characteristic of the Anthropocene's post-1950 "great acceleration", leading to a radical transformation in how humans inhabit the planet and interact with biodiversity[1,2]. The urbanisation of landscapes and lifestyles constitutes one of the most serious threats to biodiversity[3], first by consuming and altering ecosystem integrity, which is the primary cause of biodiversity decline[4]; second by distancing humans from the living world, driving a vicious cycle of extinction of our experiences of nature[5], which is acknowledged by conservation and sustainability scholars as a key threat to biodiversity commitment[6,7]. In the face of climate change, the liveability of cities has been made difficult by the lack of green space in urban planning[8]. To meet these needs, nature-based solutions (NBS) are increasingly being implemented[9]. NBS aim for long-term sustainability through ecological, social, and economic integrated solutions, leveraging the interconnectedness of ecosystems and fostering local community engagement[10,11]. Tipping points are critical concepts in the context of NBS because they highlight the urgency and potential effectiveness of these solutions to prevent sudden and irreversible changes in socio-ecosystems[9,12]. Identifying local and operational (plot-scale) socio-environmental tipping points in urban planning is fundamental as gradual urbanisation drives shifts in city-scale and planetary dynamics over time[13], representing a downscaling strategy within the planetary boundary framework[14]. For biodiversity conservation, urban ecologists stress the urgent need to expand green spaces[15] and living soils which are essential for ecosystem development and their many co-benefits[16]. More space for living organisms means more biodiversity, supporting complex urban ecosystems and ensuring resilient ecosystem services[17], human well-being[18] and reconnection with nature[19]. We posit that urban morphology changes (i.e. the physical structure and spatial organisation of cities, including their layout, land use patterns and architectural features) affect local environmental factors like human pressures and climate, leading to greening tipping points in urban socio-ecosystems. Local urban development impacts soil and microclimate conditions, leading to sudden and often irreversible changes in ecosystem states, such as the transformation into bare ground. These changes also impact the ecological functioning of nearby green spaces, making them more vulnerable to similar shifts, as feedbacks increase urban heat islands and concentrate human usage and pressures on the remaining green spaces, reducing also ecological connectivity. This, in turn, leads to less greening, lower biodiversity and decreased resilience.

Land take and soil sealing due to urbanisation are major environmental concerns[20] that stimulate research in urban morphology. Compact

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development models proposed densification to limit urban sprawl and improve regional ecological connectivity[21]. However, there is an ongoing debate among researchers and practitioners about the benefits and negative effects of densification[22], highlighting the need for metrics to evaluate the real environmental value of urban forms[23]. Proposals from multiple disciplines have been put forward to solve the "compact city paradox"[24,25] as densification has often led to vegetation loss[26] and opposition from citizens[27]. In response, urban planners and researchers have made initial recommendations for vegetation, such as a >9 m^2 of green space per inhabitant[28] or >45% vegetation at the neighbourhood scale[29]. Given that individual housing is a major driver of suburban land take[30], multi-family residential (MFR) housing must address the dual challenge of a compact (dense) but more desirable (green) city. Beyond saving land from sealing, implementing NBS in MFR[31] must better meet city dwellers' aspirations[32] for a better living environment with large and well-designed green spaces[33] that can also mitigate climate change directly where people live. These shared green spaces can offer daily interactions with nature, significantly improving well-being[34] and commitment to biodiversity preservation[35]. MFR can thus support sustainable lifestyles that reconnect urban areas and urbanites with the biosphere[36] while fostering social inclusivity. These socio-ecological connections provide fertile ground for the emergence of community narratives[37] that bolster collective environmental adaptability and resilience[38]. Statistics on MFR and their dynamics are lacking in many regions, but in European Union and OECD countries, >45% of the housing stock is typically in MFR[39], with variations ranging from 5% in Mexico to 77% in South Korea. The rising global proportion of MFR in new housing, seen in both Western countries (e.g., France in 2021, where MFR was twice the rate of individual housing) and many emerging countries, presents an opportunity to implement sustainable urbanism. However, urban form's operational guidelines with data-based evaluation of the sustainability-liveability balance are lacking[40].

Empowering transitions in practices can be facilitated by regulatory tools for effectively implementing, monitoring, and assessing NBS. These tools ensure NBS achieve their goals, adapt to changing conditions, and provide expected benefits to both ecosystems and communities. Local urbanism plans serve as the fundamental policy framework for driving transformative shifts in socio-ecological urban systems[41,42]. Enacting local regulations regarding land rights can expand and equitably distribute open spaces, creating opportunities for thriving green areas and bringing NBS transformations to fruition with environmentally just transitions. Recently, regulatory tools called vegetation coefficients have emerged as an operational plot-scale planning strategy to provide a minimal green ratio in each new development, as incremental changes lead to significantly greener built areas. In European cities, local authorities increasingly mandate these coefficients, reflecting growing interest and commitment in recent years[43]. Among the various emerging coefficients, Plot Greening which measures plot-scale ground vegetation cover, offers an objective and quantitative basis for assessing ground greening. Vegetation coefficients can effectively curb the loss of green spaces if carefully evaluated before application. However, current values are often set based on planners' opinions and beliefs[29] rather than data and impact studies. This lack of evaluation can lead to weak environmental goals and efficiency. A quantitative assessment of the supposed dilemma between density and greening, along with a comprehensive review of urban density, morphology and landscaping practices, is crucial. This supports the effectiveness of policymaking to achieve urban resilience and provides "how-to" morphological guidelines for practitioner engagement.

The paradox of sustainable urbanism hinges on balancing densification (i.e. low urban sprawl[44]) and vegetation (i.e. high supply of green space). For urban planners, balancing these two injunctions is difficult and often depicted as a true dilemma[45]. Consequently, greening is regularly relegated to the background in favour of housing production leading to "grey" densification[46]. Maintaining a stable supply of vegetation in dense residential areas is a major planning debate[47] and this paradox is a crucial issue for the adaptation of liveable cities and the global coexistence of humans with biodiversity[48]. In the current state of knowledge, reconciling density (FAR: floor area ratio, i.e., the ratio between total floor area and plot area[49]) with greening remains elusive[43]. The lack of systemic studies of urban morphology and environmental benefits has been highlighted[40] and calls for the study of fine morphological metrics and mediating variables to be related to scale and context[45].

Among the urban form metrics, open-space ratio (OSR, defined as the ratio of unbuilt area to the total floor area) has recently been suggested as a potential indicator for identifying tipping points related to biodiversity and ecosystem services capacity[40] as this metric encompasses both open spaces supply and the potential pressures they face[50]. Higher OSR, for a given density, indicates a slender building morphology, thus a higher open-space coverage and a higher open-space supply per inhabitant. This, in turn, mitigates open-space overuse and overcrowding, which is favourable for high open-space greening (OSG). Conversely, low OSR may lead to soil sealing and bare ground, which would represent a tipping point in ecosystem states that is difficult to reverse without extensive human interventions. Currently, urban densification occurs through infill construction and the addition of extra floors to existing buildings, reducing OSR at the plot or city scale and potentially crossing critical tipping points. OSR serves as a promising metric for achieving density alongside enduring greening. Identifying "qualitative density" tipping points in the balance between open-space area and floor area is essential for shaping urban morphology through effective regulations, guiding cities toward *safe operating urban morphology*.

The aim of our study is first to address the paradox of densification and greening by conducting a systemic assessment of the interplay and relative importance of urban density, morphology and landscaping in the supply of durable green spaces. This framework enables the modelling of Plot Greening from a comprehensive perspective, moving beyond the narrow density-greening dualism to provide operational insights. This analysis of greening determinants is taken further by testing relevant plot and neighbourhood context factors that could influence landscaping greening. We assume that OSG may be influenced by morphology, as suggested earlier (increasing potential pressures when OSR is low), as well as multiple plot and neighbourhood context factors related to spatial, temporal, and socio-economic contexts: plot size and slope, as large plot area and strong slope could restrict soil sealing due to high economic cost; spatial context, as neighbourhood density and greening may shape urban identity and influence planning decisions to fit accordingly; temporal context, as plot and neighbourhood construction year may influence initial greening and legacy effects[51]; socio-economic context, as neighbourhood education level may influence luxury effects[51] (see Supplementary Table 1 for context variables calculation and sources). Figure 1 summarises the conceptualisation and the hypotheses tested in the study. Second, we modelled the relationships between density, morphology, and greening to identify thresholds and establish a framework to calculate achievable Plot Greening for any given density-morphology combination. Finally, we provide recommendations for urban planners and outline a panel of urban morphologies that strike a balance between density and greening across various levels of density and building height, focusing on sustainable mid-rise structures (4 to 12 storeys) to align with low carbon emissions[52,53]. We simulate the potential co-benefits (gains in total floor area, vegetation area, distribution and equity) that could have been achieved in the past by adopting any of the outlined morphologies. Complementary to future guidelines on operational morphology, we create a strategic map of opportunities to durably regreen existing MFR plots.

Our study was conducted across the semi-rural to dense-core morphological spectrum of a medium-sized European metropolitan area (Lyon, France, and its 58 surrounding municipalities, Fig. 2). We compiled a 1-metre resolution dataset of all MFR units built between 1918 and 2018 (11,593 plots). Previous studies about dense and green have often been carried out at neighbourhood-scale[29] or within urban blocks[47], which might limit their relevance to the application as construction design and everyday management are implemented predominantly at the plot scale. By working at this scale, our study enables data-driven operational recommendations

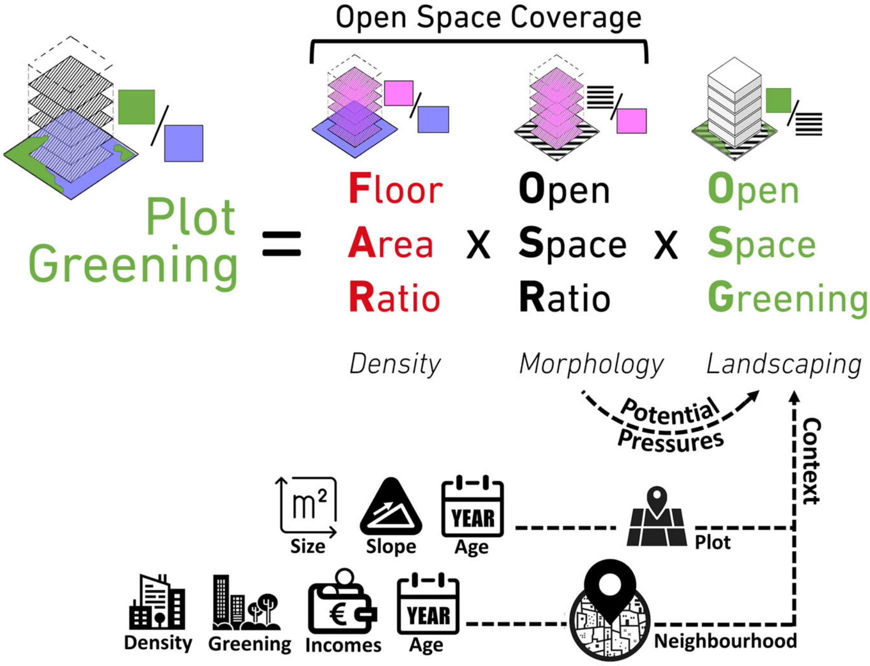


Fig. 1 | Synopsis of the study: conceptualisation and analytical framework for addressing the densification–greening issue. Plot greening is decomposed into its geometric components: density, morphology and landscaping (FAR, OSR, OSG). Landscaping variations are assumed to be related to morphological and contextual factors. These factors (dashed arrows) will be examined through empirical investigation using Random Forest modelling to provide a holistic understanding of Plot Greening variation. Metrics relationships and computations from raw data are detailed in Supplementary Figs. 1 and 2.

and a morphological benchmark of *safe operating urban morphologies* regardless of location, for all planners involved in urban sustainability.

Results

Density–greening balance

Density, measured by FAR, varied from nearly 0 to >6, while Plot Greening varied from 0 to >80%. Plot greening decreased with increasing FAR (Fig. 3), e.g. at FAR = 1 and FAR = 4 Plot Greening medians are, respectively, 35% and 10%. However, Plot Greening varied broadly around that trend, e.g. at FAR = 1 about 95% of plots have 0–60% Plot Greening and at FAR = 4, 95% of plots have 0–40% Plot Greening.

Comprehensive greening determinants

To elucidate the variability in Plot Greening, we employed Random Forest algorithms to assess the relative variable's importance, allowing for the exploration of potential non-linear relationships and covariances among variables. Three models were integrated following the framework illustrated in Fig. 1.

Model 1 (M1) takes Plot Greening as the outcome of the product of open-space coverage and open-space greening (OSG). Then, open-space coverage, a component of M1, is determined by the product of FAR and OSR, as elucidated in Model 2. Model 3 (M3) delves into the factors influencing OSG, incorporating morphology and various contextual elements spanning spatial, temporal, and socio-economic dimensions. These contextual factors are assessed relative to the plot and neighbourhood scale, as detailed in Supplementary Table 1, which provides calculations and sources. By combining these models, we aimed to capture the intricate interplay of variables shaping Plot Greening variance and to discern the relative importance of each variable within this multifaceted framework.

The Sankey diagram in Fig. 4 illustrates the breakdown of variance decomposition. Plot Greening is explained 40% by open-space coverage and 60% by OSG. FAR only explains 6% of Plot Greening, whereas OSR emerges as pivotal, explaining 43% of the variance. When combined, FAR and OSR clarify 48% of Plot Greening. The remaining OSG variance, independent of FAR and OSR, is largely attributed to landscaping, explaining 52% of Plot Greening. However, only a portion of OSG variance is explained by contextual factors such as plot size, slope, spatial context (neighbourhood greening and density), temporal context (plot and neighbourhood construction year), and socio-economics, collectively amounting to 20%. Despite these contextual factors, a significant portion (53%) of OSG variance remains unexplained. Notably, OSR and OSG together account for 94% of the variance in Plot Greening, underscoring the importance of morphology and landscaping as primary determinants in shaping Plot Greening outcomes.

Sustainable morphologies

Recommended regulatory thresholds for Plot Greening should align with both achievable and ecologically sound objectives. To our knowledge, only one empirical study has assessed urban residential ecosystem services capacity and recommends >45% neighbourhood greening for substantial heat mitigation and biodiversity benefits[29]. Considering that roads occupy >5% of neighbourhood land cover, we propose setting Plot Greening >50% as an operational target.

To establish morphological recommendation thresholds aligned with the Plot Greening target, it is crucial to thoroughly unravel the relationship between OSR, Plot Greening and OSG: while OSR and OSG together explain 94% of the variance in Plot Greening (Fig. 4), they may exhibit thresholds. As can be gathered from Fig. 5a, the Plot Greening >50% target is rarely achieved (<5%) when OSR < 0.3 but becomes more common above this value. Thus, OSR >0.3 could be a tipping point for defining sustainable morphologies and regulatory thresholds. To better understand the drastic decline in Plot Greening when OSR < 0.3, we plotted OSR vs. OSG (Fig. 5b) as OSR is presumed to indicate potential pressures on OSG. OSG reaches up to 87% when OSR >0.2, but at OSR < 0.2, OSG collapses to 0. However, even when OSR >0.2 is achieved, OSG exhibits considerable variability: 5th and 95th percentiles are respectively <10% and >85%.

In order to delineate sustainable morphologies, we modelled achievable Plot Greening ($PG_{\text{potential}}$) for any given density-morphology (FAR-OSR) combination such as:

$$PG_{\text{potential}} = FAR \times OSR \times OSG_{\text{potential}} \quad (1)$$

$OSG_{\text{potential}}$ is defined as the highest achievable OSG depending on OSR and is set at the 95th percentile to exclude outliers. $OSG_{\text{potential}}$ follows a logistic function (Fig. 5b), adjusted as follows:

$$OSG_{\text{potential}} = 0.87 \times (2/(1 + \exp^{-OSR \times 24}) - 1) \quad (2)$$

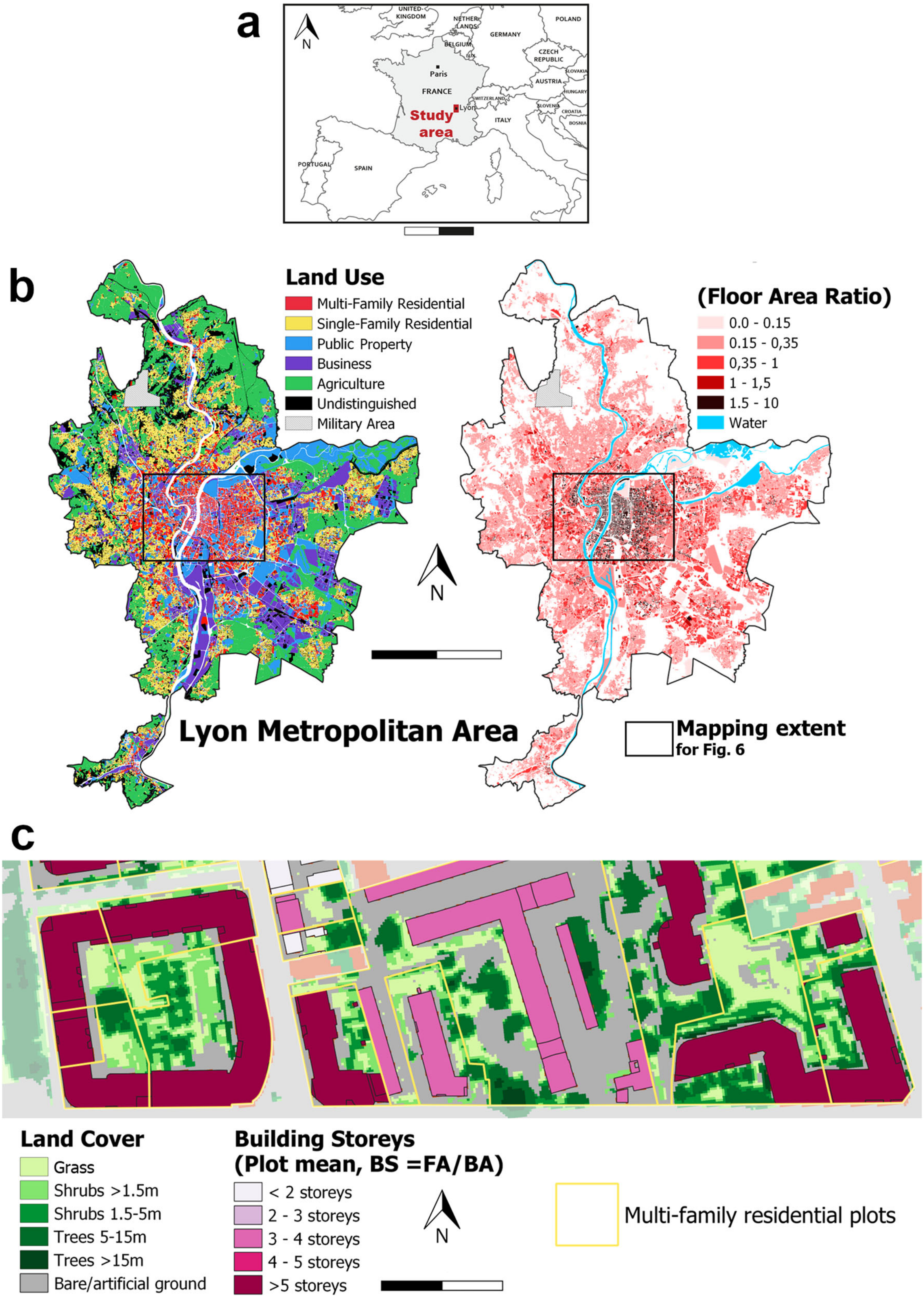


Fig. 2 | Studied territory and plot-scale data aggregation. **a** Location of the Lyon metropolitan area (France). The scale bar is 500 km. **b** Studied territory land use and density. Land use classification was operated from administrative fiscal data[83] allowing plot-scale screening according to housing, floor area uses and property types. Multi-family residential plots have ⩾3 apartments, >70% of housings are apartments and >70% of floor area is residential[82]. Density (floor area/plot area) was also computed using these administrative fiscal data[83]. For the sake of readability, we have mapped to a restricted extent several indicators in the results section (Fig. 6), comprising the entire dense urban centre and the inner suburbs. The scale bar is 10 km. **c** Close-up land cover and density maps of studied multi-family plots[83]. The scale bar is 50 m.

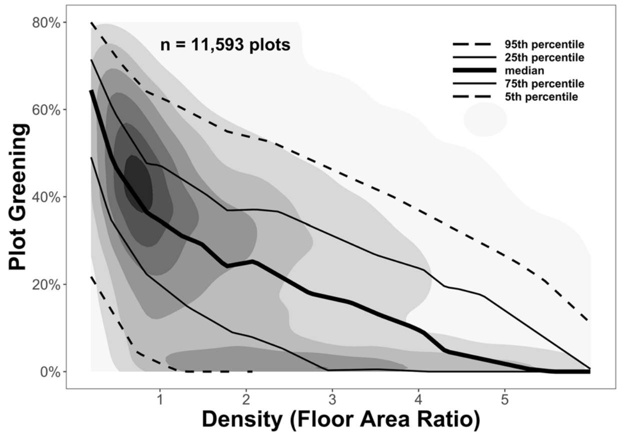


Fig. 3 | Density–Plot Greening relationship. The statistical distribution of Plot Greening for a given density is displayed with moving median, 5th, 25th, 75th and 95th percentiles to illustrate its variability. The grey scale background shows the Kernel density estimation of plot occurrences.

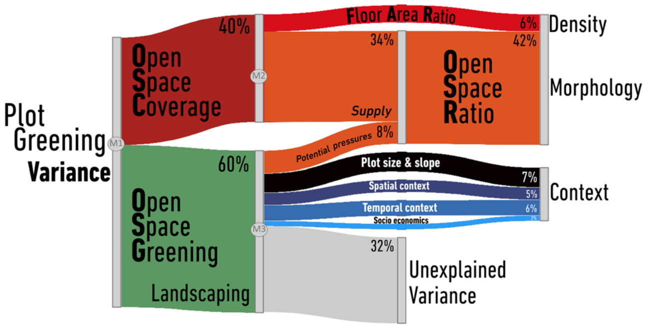


Fig. 4 | Sankey diagram of Plot Greening variance decomposition. Random Forest Machine Learning algorithms were fitted following three models to build a comprehensive tree of determinants and assess Plot Greening variance explained by each variable (%) (models raw results tables available in Supplementary Fig. 3). Model 1 (M1): Plot Greening depends totally on open-space coverage and OSG. M2: open-space coverage depends totally on FAR and OSR. M3: OSG is assumed to be influenced by morphology, as low OSR may increase potential pressures resulting in overcrowding overuse (footfall) and potential conflicts of use (services implementation), as well as multiple plot and neighbourhood context factors related to spatial, temporal, and socio-economic contexts: plot size and slope as large plot area and strong slope could restrict soil sealing due to high economic cost; spatial context as neighbourhood density and greening may shape urban identity and influence planning decisions to fit accordingly; temporal context as plot and neighbourhood construction year may influence initial greening and legacy effects[51]; socio-economic context as neighbourhood education level may influence luxury effects[51].

Using Equs. (1) and (2), the spectrum of morphologies and densities that can reach $PG_{potential} > 50\%$ is indicated in green tones in Fig. 5c. According to sustainable considerations for high density (FAR >1.5 compatible with contained urban sprawl) while excluding high-rise buildings (storeys < 12 compatible with contained carbon emissions), PG >50% target is achievable when OSR >0.3 and building storeys >4. These sustainable morphologies are illustrated with 3 examples along the density-height range (Fig. 5d), according to mid-rise building height (4, 8 and 12 storeys) and their resulting FAR density (1.5, 2 and 2.5).

Digitally replacing all MFR plots in the study area with one of the three sustainable morphologies illustrated in Fig. 5d does not result in any significant decrease in the density of the studied area. Following any of these 3 sustainable morphology recommendations (outlined in Fig. 5d) could have resulted in a gain of both floor and vegetation area of up to 125% in any given year (Fig. 5e). Not following such guidelines since 1918, has resulted in achieving only 50% (13/26 m^2) of the greening potential per apartment today, and in a 20% higher inequality in green spaces distribution (Fig. 5f). The practices observed over the most recent assessed period (2008–2018) indicate a worsening trend: from 16 m^2 to 13 m^2 greening per apartment over 10 years.

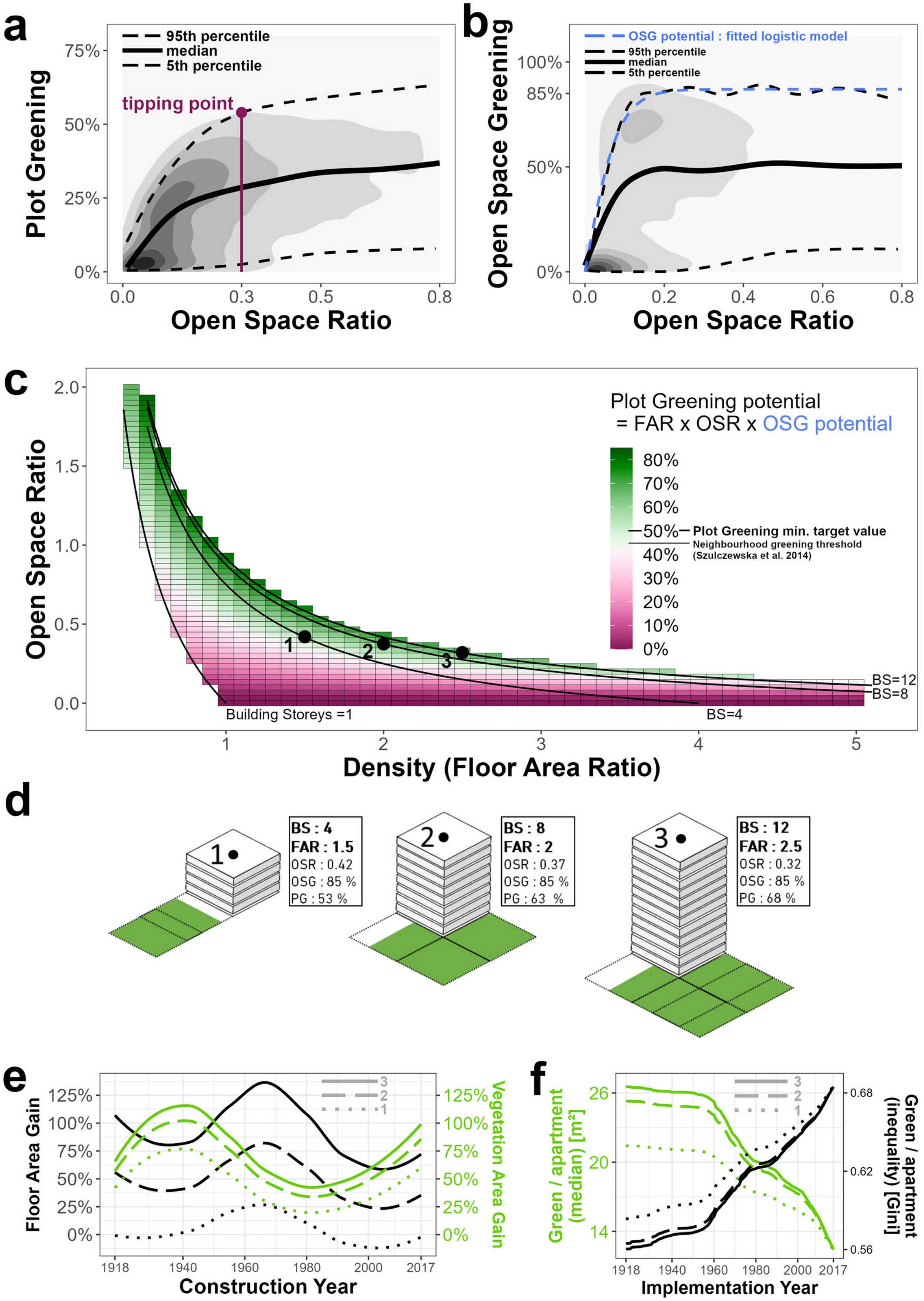
(Re)greening open spaces

There is considerable short-term potential for regreening existing open spaces to retrofit and adapt the urban environment without modifying existing buildings because OSG (independently of morphology) explains 52% of Plot Greening (Fig. 4), and when OSR >0.2, OSG = 87% was found technically achievable while the median value is only 50% (Fig. 5b). Based on plot's OSR and FAR value, $PG_{potential}$ formula (Equs. (1) and (2)) was used to compute for each plot the PG regreened value. Gains from such digital retrofitting of open spaces are important but differ spatially. Greening-oriented open-space design, without altering building morphology, could have resulted in a vegetation area increase of 20–60% in any given year (Fig. 6c). Insufficient greening of open spaces in the past, has resulted in a deficit of more than 40% in vegetation per apartment and a 6% higher level of inequality (Fig. 6d). The regreening potential of the historic city centre is very limited, despite low OSG (Fig. 6a), which is due to OSR < 0.2 (Fig. 6b) or low open-space coverage. The most significant Plot Greening gains are located in the inner suburbs (Fig. 6b) thanks to OSR >0.2 and high open-space coverage.

Discussion

Our investigation of 11,593 MFR plots in the 59 municipalities of the Lyon urban area has revealed the critical importance of morphology and landscaping in achieving high density and greening within the mid-rise sustainability scope. Morphology must ensure a minimum provision of open spaces per floor area to enable high open-space supply and greening. Once these prerequisites are met, effective greening efforts must be implemented through landscaping practices to maximise their potential. The $PG_{potential}$ model predicts the achievable greening for any given density-morphology setup, providing key insights for planners. This offers straightforward regulatory requirements for future planning and strategic maps for present regreening, enabling urban adaptation to unlock and expand the ecological potential of green spaces on private residential land[54].

The dilemma between density and greening depicted by researchers and urban planners was found to be very weak because FAR only mattered for 6% of the final Plot Greening. As previously suggested[47], there is no single optimal residential density for maximising the supply of green space, as it also depends on morphology and landscaping. As such, we clearly demonstrate the inoperability of density-based operational recommendations to control greening. The present density-greening study develops metrics and scales specifically designed to align with operational and regulatory language and frameworks. OPR, as recently proposed[40], appears to be a fundamental metric for designing and managing urban morphologies with high ecological potential and durable greening. In balancing open-space area with the total floor area, OSR explained Plot Greening five times better (42~~3~~% of Plot Greening variance explained) than FAR because of its incidence on open-space coverage (34%) and potential pressures on OSG (+8%). We posit that these potential pressures may arise from conflicts of use (such as services requiring artificial ground like parking lots or fire access routes), or later shrinkage caused by overcrowding usage pressures (resulting in footfall leading to bare ground). These potential pressures mediated by OSR are crucial sustainability indicators, demanding considerable caution in light of climate change and evolving green space usage related to residents' expectations. The empirical evidence of OSR tipping points enhances our understanding of how urban morphology influences OSG supply and durability. OSR serves as a "qualitative density" and helps reveal the critical balance needed between open-space coverage and density for sustainable greening, green space availability per inhabitant and green space resilience. These findings are of major significance for planners to delineate *safe operating urban morphology* and engage in sustainable practices. In our study, we found that designing operational morphology



with an OSR >0.3 is a fundamental prerequisite for achieving durable Plot Greening >50%. Open-space greening remains an important factor in achieving high Plot Greening: even when OSR >0.3 is reached, OSG was found to be extremely variable (0–87%, median 50%). OSG variance, regardless of density and morphology, accounts for 52% of Plot Greening but only 38% of it is explained by contextual factors related to spatial, temporal, and socio-economic contexts such as plot size, slope and construction year; neighbourhoods' density, greening, construction year and education level. Thirty-two percent of Plot Greening variance remained unexplained, suggesting other factors additionally influence OSG: we posit cultural aspects such as past and current landscaping practices, as well as residents' aesthetic preferences and cultural background. Notably, no OSG

Fig. 5 | Sustainable (dense and green) morphologies referential and models outlined with associated benefits on the study area. a Plot Greening distribution depending on OSR. OSR = 0.3 is defined as a tipping point because Plot Greening drops sharply when OSR < 0.3 and OSR >0.3 enables the highest achievable Plot Greening (set at 95th percentile) to reach >50% Plot Greening target. The grey scale background shows Kernel density estimation of plot occurrences. **b** OSG distribution depending on OSR. OSG potential is the highest achievable OSG (set at 95th percentile) depending on OSR and follows a logistic model: $OSG_{potential} = 0.87 \times (2/(1 + \exp(-OSR \times 24)) - 1)$. The grey scale background shows the Kernel density estimation of plot occurrences. **c** Plot Greening $_{potential}$ model predicts the achievable greening for any given density-morphology (FAR-OSR) setup. Green tones show morphologies matching the >50% Plot Greening target. Isocurves show building height (storeys). **d** Sustainable morphologies panel balancing density and greening with variable density and building height, focusing on mid-rise buildings (4 to 12 storeys) to align with sustainable carbon emissions concerns[52,53]. **e** Simulations of annual benefits in vegetation area and floor space in the study area, if any of the three sustainable morphologies outlined above were applied instead of the original construction made during the given year. **f** Simulations of per apartment vegetation area available (median and equality in distribution) in the study area if any of the three sustainable morphologies outlined above had been adopted in previous years and systematically applied in subsequent operations.

technical constraints were identified in the context factors, indicating a broad scope for >85% OSG improvement. Achieving an OSG >85% is the second prerequisite to ensure a high Plot Greening, as up to 94% of Plot Greening is determined when OSR and OSG are set together.

Our panel of 11,593 study plots showed a wide range of FAR-OSR combinations, encompassing the global variability of mid-rise buildings (<1% have >12 storeys). This aligns with carbon and social sustainability concerns, as high-rise buildings entail higher energy and CO_2 emissions (embodied and operational carbon)[52,53] and elevated economic costs, rendering them non-inclusive[55]. Balancing density and greening does not mean uniform optimisation and our findings support urban form diversification, showcasing a range of plot morphologies achieving sustainable Plot Greening (>50%) with OSR >0.3, spanning from density 1.5 with 4 storeys to density 2.5 with 12 storeys. Our guidelines focus on morphology at the plot level, leaving plot layout aside, which allows planners to adopt various urban forms through urban master plan zoning. These guidelines also give complete freedom to architects for building and open-space forms. These recommendations for practitioners are in line with authors who emphasise the importance of avoiding one-way guidelines[47] and consider urban biocultural pluralism and heterogeneity[56]. Scaling up from plot morphologies to neighbourhood urban form involves additional land take due to road networks, which could be minimised according to super-block[57] or fractal development[58].

Focusing on mid-rise buildings may address concerns about building height in the acceptance of urban forms[59]. But, as urban forms cannot be considered sustainable if they are not fully accepted by people[60], these results emphasise the importance of revisiting the social acceptance of density by decoupling height and OSR. We expect that high OSR associated with high-quality green spaces could be accepted by urban dwellers at density levels that would otherwise be rejected. This calls for social research to assess this hypothesis, because, to our knowledge, there is no morphological acceptability study dedicated to OSR, although architects are increasingly promoting their projects on the basis of 'qualitative density' indexes balancing open or public spaces versus floor or private areas (pers. obs.). While the literature on this topic is scarce, some economic studies seem to support this hypothesis: for instance, in Singapore, MFR received a higher hedonic value when >63 m^2/inhabitant[61]. Sustainable morphologies also appear economically viable, with 10% of surveyed plots in our study having OSR >0.3 and FAR >1.5 over the past 20 years. Social viability raises another concern, as green and sustainable urbanism can increase attractiveness and real estate value[62], potentially leading to gentrification[63]. This can be addressed through political commitment, regulatory tools like housing mix[64] or rental price[65] regulations, and alternative housing ownership models like Community Land Trusts.

Our results provide a quantitative and comprehensive assessment of urban density and morphology on the supply of green spaces. The comprehensive PG $_{potential}$ model predicts the achievable greening for any given density-morphology (FAR-OSR) setup, which provides a key insight for planners seeking a reference framework for sustainable planning simulations. The sustainable morphological spectrum, ensuring balanced and durable greening alongside density, could be effectively regulated through straightforward rules incorporated into urban planning documents: OSR >0.3 and OSG >85% which results in a final Plot Greening >50%, a threshold with substantial benefits for climate change mitigation and biodiversity[29]. Additional sustainable considerations for low urban sprawl and low carbon emissions entail substantial density (1.5 < FAR < 2.5) and mid-rise buildings (4 to 12 storeys). Given evolving green space pressures due to climate change and shifting expectations of urbanites regarding green space usage, integrating the OSR threshold into urban regulations with safety margins is crucial. Recommendations to urban planners must be stringent to address the inherent uncertainties of these global changes. We propose setting a benchmark for future urban development with an OSR >0.5 rather than an OSR >0.3. This OSR safety margin should account for climate and open-space usage differences in various urban contexts, strengthening guidelines' replicability and validity until additional studies are conducted in other regions worldwide to compare the OSR-OSG threshold value. OSR >0.5 deserves a prominent place in planning documents to define *safe operating urban morphologies*, as it is a prerequisite for achieving sustainable greening and ensuring resilience against evolving usage pressures combined with the impacts of climate change. Requiring OSR >0.5 and OSG >85% in mid-rise (4 to 12 storeys) buildings provides straightforward and universally applicable guidelines for achieving sustainable greening objectives and reaping associated co-benefits. Regreening existing MFR open spaces offers a complementary and efficient strategy to adapt cities, as OSG, regardless of morphology, accounts for 52% of Plot Greening variance. Our analysis suggests minimal dependence of OSG on technical, legal, and social constraints, making 85% open-space greening a realistic guideline for practitioners. We argue that changes in landscape practices are mainly slowed down or countered by cultural biases. However, the transition towards sustainable and biodiverse landscapes is now a growing popular concern, which could also be supported by financial incentive policies to retrofit plots[66]. Producing maps showing where and how much green space cover can be gained is a concrete way of tackling the challenge of unlocking the ecological potential of green spaces on private residential land. In practice, however, the feasibility of MFR regreening depends on the initial services implemented, landscaping arrangements, and the subsequent development of usage patterns. These social and economic constraints must be assessed on a case-by-case basis, necessitating social facilitation and economic support from local authorities. Such an efficient urban transition must follow social pathways based on community-driven initiatives that engage, educate and empower residents with opportunities to deepen their understanding of, and attachment to, their local environment and the biosphere[36]. These guidelines would inherently contribute to increased equity in the social distribution of vegetation while cultivating resilience and sustainability within the constraints of everyday life. This local approach should constitute a promising NBS as it bolsters the sense of place, interest and care of urban green commons[38,67], a bottom-up catalyst for residents to act on concrete and direct transformations within the spaces they inhabit[36]. From the perspective of biodiversity conservation, these guidelines can promote the implementation of a land-sharing strategy and address the need for proximity ecosystem services for climate change adaptation in cities. They contribute to the hybrid infrastructure strategy[68] and foster day-to-day interactions with biodiversity which are essential for commitment to the preservation of biodiversity.

While our results provide a comprehensive basis for green space supply and a ready-to-apply range of sustainable urban morphologies,

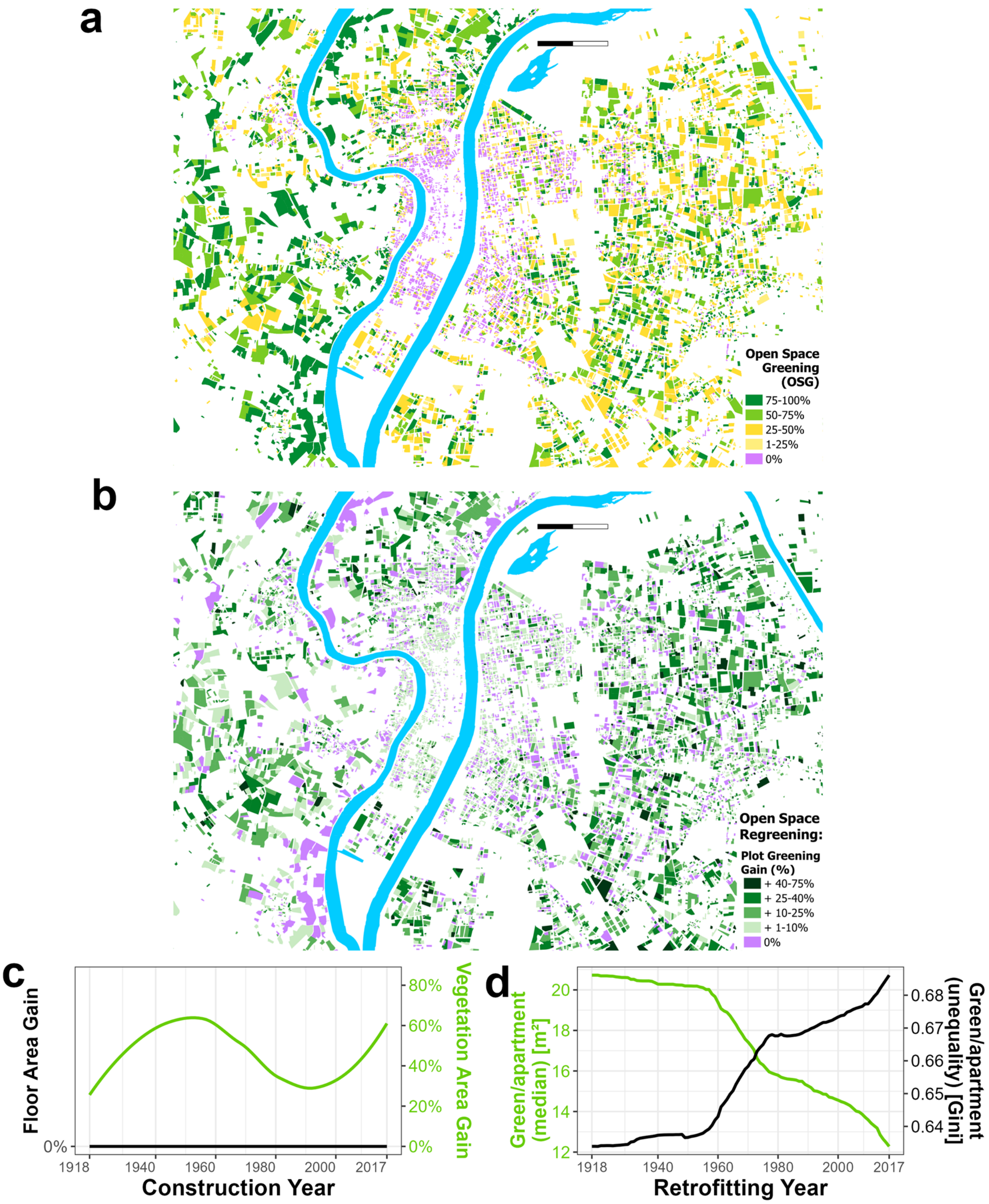


Fig. 6 | Open-space durable regreening scenario. **a** Present OSG. The scale bar is 1 km. **b** Plot Greening Gain scenario when open space is regreened, reaching Plot Greening $_{\text{potential}}$ based on plot FAR and OSR (cf. Fig. 5b, c and Eqs. (1) and (2)). The scale bar is 1 km. **c** Simulation of vegetation area gains on the study area, following the open-space regreening scenario and according to plots construction year. **d** Simulations of gains per apartment vegetation area available (median and equality in distribution) in the study area according to the open-space regreening scenario i.e. if all operations achieved after a cut-off year were retrofitted.

further research should address the ecological quality of these spaces for biodiversity. Biodiversity data across numerous taxa would be crucial to deepen our comprehension of ecological suitability[69] and refine urban policies to reconcile density with greening and biodiversity[46]. This coupling of systemic urban morphology with in-depth ecological studies is currently the focus of our forthcoming research and could provide a definitive validation of recommendations for sustainable and ecological urbanism that guarantees sufficient capacity and resilience of ecosystem services, going beyond merely ‘green’ urbanism.

Furthermore, this could provide additional evidence for or against the threshold of >50% Plot Greening for biodiversity and ecosystem services, as observed by Szulczewska et al.[29], which we used as a basis and target reference throughout this article. Conducting participatory biodiversity inventories with residents would provide an additional opportunity to implement NBS and move towards transformational research[70] as this could feed collective co-constructions of sense of place[11,71,72] and nature connectedness. These methods serve as fertile ground to empower people through collaborative practices[73–75] involving urban planners and decision-makers in sound citizen science[76,77].

Methods

Analyses were carried out on all extant multi-family residential plots built from 1918 to 2017 in the Lyon metropolitan area (11,593 plots) including both condominiums and social housing. The dataset combines remote sensing and administrative fiscal data on housing, aggregated at the plot level. The base year is 2017 because it was conditioned by the most recent multispectral aerial and lidar imagery that allowed for 1-metre spatial resolution vegetation mapping.

Study sites

The metropolitan area of Lyon is the third largest urban area in France (1,411,571 inhabitants, 538.4 km^2). Metropolitan attractiveness policies and economic circumstances have led to a demographic balance over the last 5 years that is 3 times higher than at the national level and drives the densification of the city[78]. 1/3 of current housing is less than 20 years old and 98% of housing created during this period are apartments. Today, more than 75% of the whole floor area production is dedicated to multi-family residential (Supplementary Fig. 4). The Lyon metropolitan area presents a broad diversity of plot and neighbourhood morphologies due to topography and rich urban history characterised by architectural evolutions and intense urban growth during the last 100 years[79] (Supplementary Fig. 5). The study area encompasses 59 municipalities ranging from semi-rural villages to dense urban centres, featuring distinct urban layouts across districts, including the historic core from the 14th century, 19th-century boulevards, 20th-century business districts and sprawling residential suburbs featuring detached houses and MFR[80] (Fig. 1). This makes both the entire area and its parts representative of numerous other small to large European urban areas, including most morphological combinations. This study is focused on a single metropolitan area to make use of unique very high-resolution fiscal and vegetation data available. The size and characteristics of the dataset should make our findings and recommendations relevant to all urban areas around the world which experience resilience and sustainability issues[42] due to urban development and climate change[81]. These concerns are also a critical issue in small to mid-sized cities[78] looking to preserve natural and agricultural land while creating equitable and affordable residential landscapes.

The definition of MFR used to identify the study plots was as follows: ≥3 apartments, >70% of housing are apartments and >70% of the floor space is for residential use. These criteria are identical to the Atlas of the Urban Fabric in the Paris Region[82]. Plots (i.e. “land property unit” which is the aggregation of adjoining parcels belonging to the same owner) were extracted from the Fiscal Land Property Dataset distributed by the French Centre for Studies and Expertise on Risks, the Environment, Mobility and Urban Planning (CEREMA)[83]. This MFR stock in the Lyon metropolitan area represented 20,906 plots and accounted for 98% of apartments (76% of the whole housing stock). From these, only plots built over the past 100 years (1917–2017) were selected to conduct statistical analyses representative of current modern practices of urban planning and building. These 11,593 plots studied covered 3400 ha and 460,000 dwellings, accounting for 85% of the land surface, 83% of floor areas and 82% of the whole MFR housing stock. 99% of the plots surveyed comprise buildings below 12 storeys, which is consistent with the sustainability concerns of carbon emissions during building construction and functioning[52,53].

Land cover data

The land cover mapping was combined from various sources. Vegetation was identified at a resolution of 1 m[84] by remote sensing with Object-Based Image Analysis[85] which involved aerial photography and LiDAR heights. Plot greening excluded green roofs, to get as close as possible to objective ground indicators. It should be noted that greening does not infer soil conditions (open ground/sealing) due to possible masking by tree crowns. Building cover was obtained from the BD TOPO data of the IGN[86]. All surfaces that were neither built nor covered by vegetation were classified as bare/artificial ground.

Density and morphological metrics

Many indicators of urban morphology have emerged due to the recent availability and quality of large-scale datasets, reinforcing the interest of researchers in buildings[87]. The set of morphological metrics used in this paper is listed and illustrated in Supplementary Figs. 1 and 2. Studying morphology required information on floor areas, provided also by the plot-scale fiscal dataset of the CEREMA[83]. Density was calculated according to floor area ratio (FAR)[49]. Morphology was assessed by OSR, a more qualitative index of density that expresses the balance between unbuilt open space and floor areas.

Densification and morphological dynamics were illustrated from the same plot-scale fiscal dataset of the CEREMA[83] which gives floor areas, their uses and the construction year, thus making it possible to calculate density and other morphological metrics and trace it back in time. Evolution of morphology and land cover in multi-family residential was seen through the plots still existing in 2017 (Supplementary Fig. 4) and shows FAR, OSR and Building Coverage having relatively coordinated upward and downward trends over time, while Building Storeys follows a distinct trend that overall increases until the 2000s, then drops and stabilises. The greening decreased drastically for constructions made within the last 10 years while the highest greening was achieved for 1980s constructions.

Plot context

Landscaping choices (such as OSG) made in each plot may vary according to numerous contextual factors. A summary of context variables investigated is available in Supplementary Table 1. At the plot scale, we retained size, slope and construction year. High plot size and slope could limit soil sealing due to high costs combined with the low benefit of sealing these surfaces. Construction years could inform about landscaping practices which evolved over time.

At the neighbourhood scale, we retained urban and landscape environments (FAR_N and OSG_N) because operations fit into the existing neighbourhood identity. Socio-economics (education level, EDU_N) could indicate different investment budgets and preferences during landscaping design and fulfilment[88] affecting OSG due to the “luxury effect”[51]. Because of the influence of housing policies and urban form prescriptions that vary over space and time, we also used the average construction year of the neighbourhood (weighted mean by the area of each plot: Y_N). The neighbourhood scale was applied following delineations established by the French National Institute of Statistics and Economic Studies (INSEE): an “IRIS” neighbourhood includes about 2000–5000~~k~~ inhabitants and is established from geographical and statistical criteria[89]. IRIS neighbourhood delineates more accurately homogeneous neighbourhood identity than raster grids and is the smallest scale available to assess socio-economic situations to a large extent without missing data due to confidentiality threshold.

Statistical analysis

Variance decomposition of Plot Greening and relative variable importance were modelled using Random Forest algorithms, which are particularly suitable to manage possible non-linear relationships or covariance between variables[90–93]. Random Forest models build a decision tree to assess the proportion of variance explained and the variable’s importance[94]. It is also important to note that RF models are not subject to overfitting. The relative importance of each variable is calculated from the Increased Mean square error (%IncMSE) also known as the mean decrease in accuracy. Variable importance is measured by calculating the difference in mean squared error (MSE) after randomly permuting the variable of interest values. It quantifies the improvement in model prediction resulting from the inclusion of the variable of interest and was developed by Strobl et al.[95] to address the bias of the mean decrease gini (IncNodeImpurity)[96].

Quantiles (5th and 95th percentile) were computed using a rolling (moving window) algorithm with a narrow 0.02 OSR bin width. The smoothed trend was then plotted using a generalised additive model. The asymptotic model of the 95th percentiles in Fig. 5b was evaluated using both asymptotic regressions:

$$y = L - L \cdot e^{-k \cdot x}$$

and logistic regression:

$$y = L \cdot (2/(1 + e^{-k \cdot x}) - 1)$$

Parameter estimations for L (the function supremum) and k (the increase rate) were made iteratively using non-linear least squares. Logistic regression was ultimately retained due to a higher R^2 value with the same number of parameters.

Scenarios for guideline implementation and regreening

Regreening scenarios were calculated based on plot OSR and FAR value: $PG_{potential}$ formula was used to compute for each plot the Plot Greening regreened value. Then, the Plot Greening regreened value was compared to the original Plot Greening value to assess Plot Greening gain (Fig. 6b). Similar comparisons between regreened value vs original value were made to assess the co-benefits in vegetation total area, distribution and equity.

Data availability

The map depicting 1 m resolution land cover data is available for consultation on this website: https://collectifs-biodiversite.universite-lyon.fr/carte-dynamique-vegetation/. The data on the 1 m resolution vegetation cover can be downloaded: https://data.grandlyon.com/portail/fr/jeux-de-donnees/vegetation-stratifiee-2018-metropole-lyon/info The aggregated plot-scale datasets are available from the corresponding author upon request, as they include data from the Fiscal Land Property Dataset[83], which is subject to publication restrictions. Original data sources are detailed in the 'Methods' section.

Code availability

The code used to generate the results in this study is available from the authors upon reasonable request. This study does not custom code or mathematical algorithm that is deemed central to the conclusions. The calculation process of metrics is detailed with equations in the main text and Methods.

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Conceptualisation: T.B., M.B., B.K. Methodology: T.B., M.B., B.K. Validation: T.B., M.B., B.K. Formal analysis: T.B. Investigation: T.B. Data curation: T.B., A.B., F.C. Writing—original draft preparation: T.B. Writing—review and editing: T.B., M.B., B.K. Visualisation: T.B. Supervision: T.B., B.K., M.B. All authors have read and agreed to the published version of the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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