

Adaptation Lock-in Shifts Justice from Allocation to Sequencing

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1 Abstract

Climate adaptation regimes unfold through sequences of decisions over decades, yet whether and how such decisions generate lock-in remain unclear. Here we use tree canopy data from Greater Sydney to analyze heat adaptation under justice principles across future climate and socioeconomic scenarios. We show that distinct justice principles embed spatial commitments that generate adaptation lock-in. As these commitments accumulate, adaptation regimes diverge, making shifts between them increasingly costly. Increasing resources do not eliminate this divergence but instead shift its dominant source from distributional justice, concerning how adaptation benefits are allocated, to procedural justice, concerning how sequencing rules govern allocation through time. These patterns hold across alternative measures of system state, suggesting that lock-in is a general property of sequential decision-making under irreversible commitments. The policy challenge therefore extends beyond identifying the optimal allocation today to determining which sequencing rules best govern transitions toward desired futures.

2 Main

Urban heat poses a growing climate risk, driven by the interaction of global warming with long-standing patterns of urban development¹⁻³. Exposure to extreme heat varies markedly across neighborhoods, reflecting differences in land cover, building density, and urban morphology, with unequal consequences for health, productivity, and livability⁴⁻⁶. Heat adaptation is therefore increasingly examined through the lens of justice, with attention to how the design and implementation of climate actions shape the distribution of risks and protections across urban communities⁷⁻⁹. Decisions about where, when, and how to deploy resources in heat adaptation projects determine who benefits from protection, who remains exposed, and how patterns of risk evolve as conditions change¹⁰.

Such decisions are not made in isolation¹¹. Heat adaptation planning unfolds through long-term policy and decision-making processes under deep uncertainty about future climate conditions, urban development trajectories, and resource constraints¹²⁻¹⁴. Adaptation is implemented through sequences of decisions in which earlier choices influence the feasibility, cost, and desirability of later options^{10,15}, making adaptation inherently procedural and path-dependent¹⁶. We conceptualize these decision sequences as adaptation regimes: persistent decision logics that govern how adaptation resources are prioritized and allocated through time. In resilience science, regimes denote stable configurations of rules and feedback that shape system trajectories and resist change¹⁷⁻¹⁹.

Over time, accumulated decisions within a regime progressively constrain which future actions remain feasible and acceptable, creating lock-ins that stabilize some responses while foreclosing alternatives²⁰⁻²³. Lock-ins develop not only from physical infrastructures but also

from institutional routines, planning standards, and behavioral norms that co-evolve over time^{22,23}. Once established, such commitments are difficult to reverse because changing direction often requires coordinated shifts in governance, finance, and social practice^{19,21,22}. A regime shift occurs when an established regime is replaced by alternative arrangements, typically demanding the reorientation of accumulated commitments²⁴⁻²⁶. We extend this concept to justice by defining adaptation regimes according to the justice principles that govern resource allocation. Regime shifts therefore entail changing justice principles while inheriting commitments established under previous decisions.

Existing research has examined lock-ins across climate and infrastructure systems, including carbon-intensive technologies, interdependent infrastructure, institutional arrangements, and long-term transition pathways^{21-23,27-29}. By contrast, the implications of lock-in for climate justice have received little attention. Studies of justice in adaptation projects typically focus on endpoint outcomes, asking whether adaptation resources and benefits are distributed equitably across places or populations^{3,30,31}. Although such studies provide valuable snapshots of distributional outcomes, they offer less insight into the procedural dimensions of adaptation, including how adaptation regimes emerge, persist, and shift through time, and how sequential decisions reshape future adaptation possibilities^{10,21,22,32}. Whereas procedural justice conventionally concerns fair participation and representation in decision-making processes^{16,33,34}, we extend it to the temporal dimension of decision-making: the sequencing rules that determine when and where adaptation resources are allocated, and thereby which options remain open to future decision-makers. We therefore ask *how sequential adaptation decisions shape justice-based adaptation regimes over time, and whether early spatial commitments generate lock-ins?*

Here, we examine justice in urban heat adaptation through a procedural justice lens, focusing on how distributive outcomes emerge and evolve across alternative adaptation regimes. Using tree canopy allocation in Greater Sydney as an empirical case, we operationalize three justice principles—utilitarian, sufficientarian, and prioritarian—under coupled Shared Socioeconomic Pathway (SSP)–Representative Concentration Pathway (RCP) scenarios and alternative allocation timelines. We show that different justice principles generate distinct spatial allocation patterns from the outset, embedding early commitments that shape subsequent regimes. We find that lock-in emerges before aggregate capacity is exhausted, because earlier allocations reorganize where feasible capacity remains, constraining the ability to reconfigure spatial allocation under alternative regimes. This mechanism shifts how justice itself evolves through time. Under limited budgets, divergence reflects how scarce adaptation resources are distributed, whereas under larger budgets, it reflects how allocation sequences constrain future options. Decision-makers therefore inherit spatially structured choice sets shaped by earlier commitments, a form of procedural injustice that endpoint comparisons alone cannot detect. Our analysis reframes justice in urban heat adaptation as a property of evolving decision

processes, showing how early allocation decisions lock cities into spatially structured adaptation futures.

3 Results

We analyze sequential, decade-by-decade tree canopy allocation decisions across neighborhood-scale microcells in Greater Sydney (Extended Data Fig 1), under three coupled SSP–RCP scenarios (SSP1–2.6, SSP2–4.5, and SSP5–8.5). Within each scenario, we evaluate three justice principles that differ in their prioritization rules (utilitarian, sufficientarian, and prioritarian), four allocation timelines (Extended Data Fig 2), and a wide range of total canopy budgets by 2100 (25 to 4,000 million m² of tree canopy). Throughout, feasibility evolves endogenously as the built environment expands and land-use constraints tighten. Tree canopy accumulates over time except where reduced by forced losses associated with urban development, and outcomes are evaluated at decadal decision points from 2040 to 2100. We then examine how regime choices shape the spatial configuration of heat adaptation resources over time, how distributive outcomes diverge or converge across canopy budgets, and how regime shifts reveal locked-in commitments.

Holding resources and external conditions constant, distinct spatial patterns of canopy expansion emerge under different justice principles (Fig. 1), isolating how alternative procedural approaches translate into spatial adaptation outcomes. Across multi-decadal planning horizons, the resulting configurations diverge in the concentration and dispersion of canopy gains. Prioritarian regimes concentrate canopy expansion in high-need neighborhoods, whereas utilitarian and sufficientarian regimes distribute canopy gains more broadly while prioritizing contrasting locations. Sufficientarian regimes preferentially allocate canopy to neighborhoods with lower pre-existing greenness, whereas utilitarian regimes prioritize neighborhoods that are already greener. These differences emerge from the earliest allocation periods, generating distinct spatial commitments from the outset. The spatial configuration established under each regime subsequently shapes all future allocations, influencing which adaptation opportunities remain available.

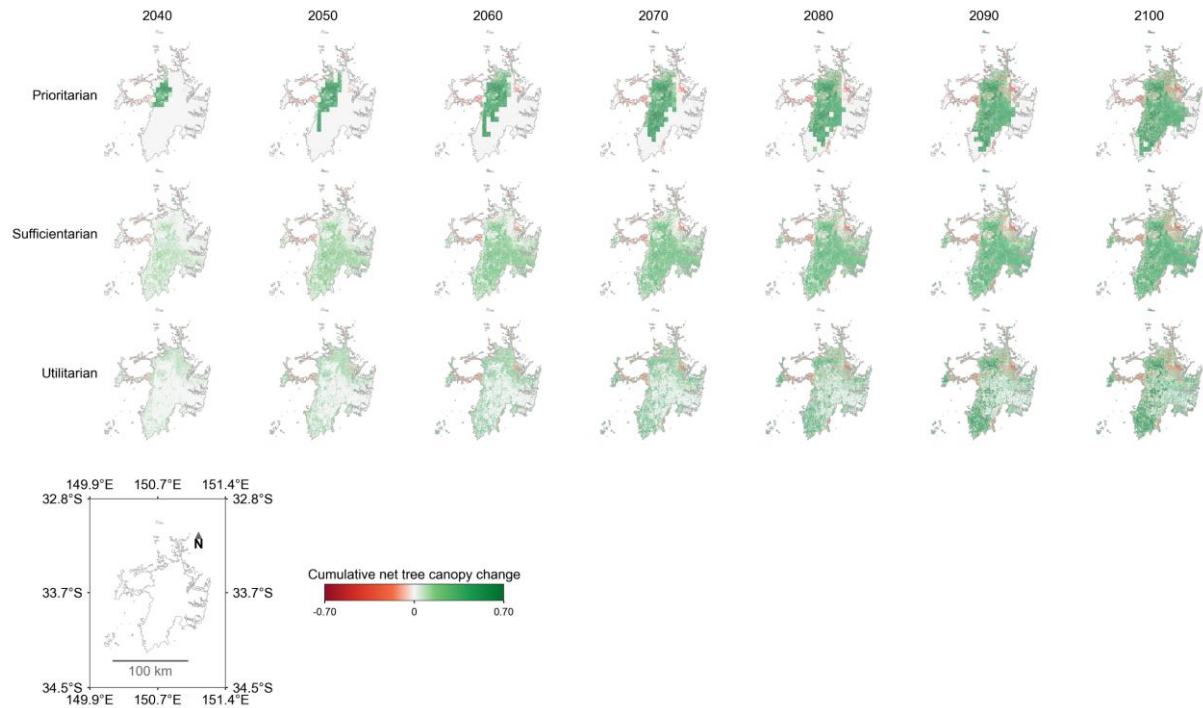


Fig. 1: Cumulative net tree canopy change by decade based on different justice principles under SSP5–8.5 with a 2,000 million m² total canopy budget and linear allocation timeline in the Greater Sydney region. Rows show prioritarian, sufficientarian, and utilitarian principles. Green indicates net gains and red indicates net losses due to urban developments.

3.1 Delayed regime shifts increase lock-in

Early allocation decisions create spatial path dependencies that become consequential when cities shift to alternative just adaptation regimes. Decision-makers adopting a new regime inherit the spatial commitments embedded by predecessor regimes, creating a mismatch between current priorities and the configuration of adaptation resources already in place (Fig. 2 and Extended Data Fig 3-5). We quantify this inherited constraint as lock-in cost: the divergence between the realized adaptation trajectory following a regime shift and the counterfactual trajectory had the alternative regime been implemented from the outset, measured across canopy budgets and regime-shift trajectories (Fig. 2a,b).

As expected for sequential decision-making under irreversible commitments, lock-in cost increases as regime shifts are delayed (Fig. 2c). This pattern reflects a mechanism that is both spatial and budgetary. Early regime shifts produce relatively small divergence because only a limited share of canopy has been allocated. As more canopy budget is committed under the incumbent regime, subsequent shifts must operate within an inherited spatial configuration that reflects its priorities. Because earlier allocations cannot be reversed, realized trajectories increasingly diverge from those that would have emerged under the alternative regime.

This divergence scales with the total canopy budgets. Larger budgets embed greater commitments before a regime shift occurs, amplifying the cumulative effects of path

dependence. Delayed regime shifts under higher budgets generate larger lock-in costs, particularly in later decades (Fig. 2c). In practical terms, the longer cities remain committed to a particular adaptation regime and the more resources they deploy under that regime, the more difficult adopting an alternative allocation logic. In this sense, earlier decisions intended to reduce heat risk accumulate into commitments that lock in the distribution of protection across neighborhoods well before the end of the planning horizon.

The observed lock-in dynamics do not depend on the choice of system-state metric. Repeating the analysis using a built-weighted canopy state metric, which evaluates canopy provision relative to the built area, where population is typically concentrated, yields the same qualitative pattern of increasing divergence with delayed regime shifts and larger canopy budgets (Extended Data Fig 6). Our results indicate that lock-in is not an artifact of how canopy distribution is summarized but a general property of sequential decision-making under irreversible commitments through which procedural justice unfolds.

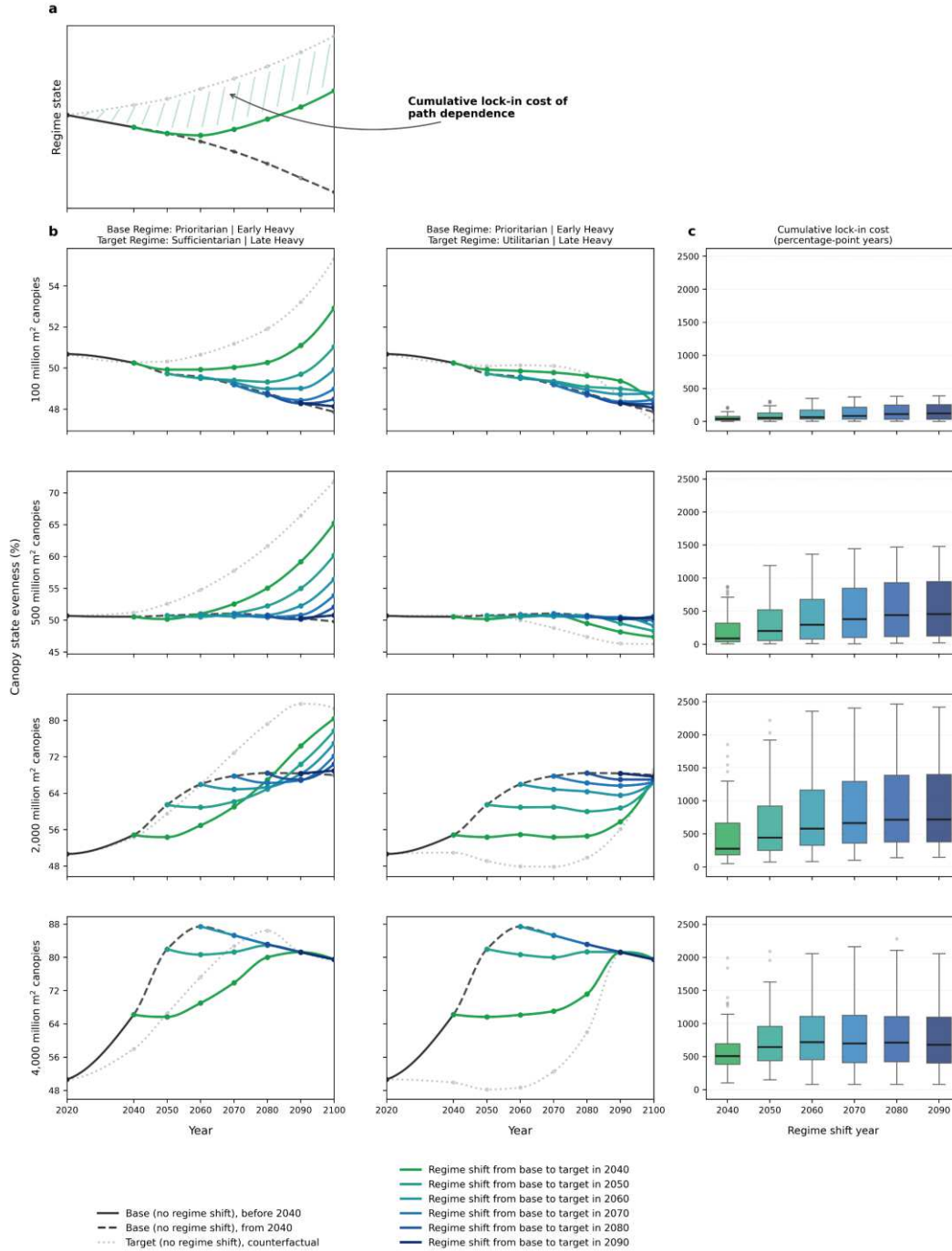


Fig. 2: Lock-in dynamics in sequential just adaptation regimes under the SSP5-8.5 scenario. **a**, Conceptual illustration of cumulative lock-in costs from path-dependent procedural decisions. Vertical gaps indicate divergence after each decision point, and the shaded area represents the cumulative lock-in cost of path dependence, reflecting the portion of system performance that cannot be recovered. **b**, Two examples of regime shift cases drawn from the full set of 132 possible shifts among 12 adaptation regimes (three justice principles $\times$ four allocation timelines; 12×11 possible base–target shifts). Branching trajectories show canopy state evenness (%), defined as $100 \times (1 - \text{Gini})$ of canopy area across neighborhood-scale microcells, under a baseline regime and alternative target regimes. Rows show increasing total canopy budgets by 2100. **c**, Distribution of cumulative lock-in costs associated with delayed shifts across all regimes. Lock-in cost is measured as the integrated area between the realized trajectory (baseline followed by the shift) and the corresponding target counterfactual trajectory from 2020–2100, expressed in percentage-point years.

3.2 Mechanisms for adaptation regime shift

To explain why delayed regime shifts generate persistent lock-in, we examine how sequential allocation decisions reshape the decision space through time. Lock-in emerges because each allocation decision modifies the spatial configuration within which subsequent decisions must operate. As canopy is progressively allocated across neighborhoods, the distribution of remaining feasible capacity is reorganized, constraining the actions available to alternative adaptation regimes (Fig. 3 and Extended Data Fig 7,8).

This divergence does not require reaching an absolute feasibility limit. Across all regime-shift analyses, the target canopy distribution remains achievable in aggregate by 2100 if all remaining feasible capacity is allocated (Fig. 3a). Instead, lock-in emerges well before absolute spatial limits are reached because prior commitments alter where feasible capacity remains relative to the priorities of an alternative regime. The binding constraint is therefore not the remaining capacity but the declining ability to reconfigure its spatial allocation, a constraint on process rather than quantity.

The dominant mechanism is the early allocation of canopy in locations that the target regime would not have prioritized at that stage, a process we define as premature commitment (Fig. 3b). As the regime shift is delayed, an increasing share of canopy becomes embedded in microcells inconsistent with the priorities of the alternative regime. Because these commitments cannot be strategically withdrawn within the procedural framework, the alternative regime must proceed through incremental additions rather than reconfiguring earlier placements. Decisions under the new regime remain possible, but become increasingly resource intensive.

The operation of this mechanism depends on the total canopy budget. Under low to moderate budgets, premature commitments substantially reduce the remaining scope for reallocation, because the budget available after a regime shift is insufficient to offset earlier placements, realized allocations remain persistently different from the counterfactual regime outcome (Fig. 3c and Extended Data Fig 9-11). As canopy budgets increase, additional allocations progressively fill the remaining feasible planting locations, reducing the consequences of earlier commitments. We term this process spatial saturation, whereby the progressive exhaustion of feasible planting locations compresses differences between adaptation regimes.

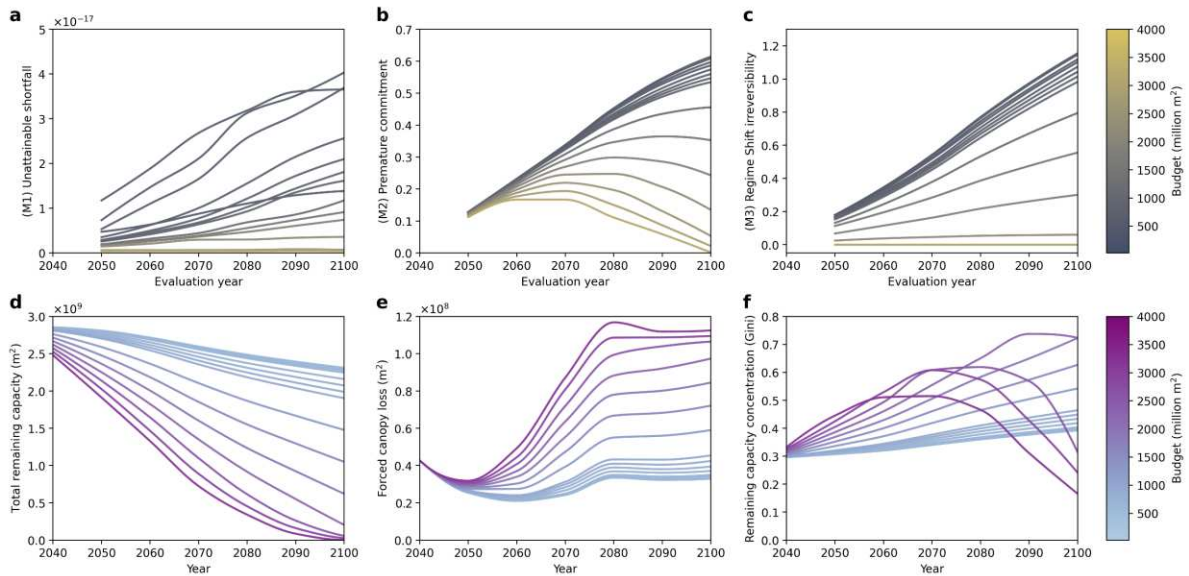


Fig. 3: Lock-in diagnostics and decision space contraction across canopy budgets under the SSP5-8.5 scenario. **a**, Unattainable shortfall shows the portion of the target canopy distribution at 2100 that cannot be recovered even if all remaining feasible capacity were used. **b**, Premature commitment shows canopy area already allocated before the shift in locations that the target regime would not have prioritized. **c**, Regime shift irreversibility shows the normalized L1 distance at 2100 between the shifted trajectory and the counterfactual trajectory that follows the target regime from 2040. **d**, Total remaining feasible canopy capacity across microcells. **e**, Forced canopy loss resulting from tightening feasibility constraints due to urban development. **f**, Spatial concentration of remaining feasible capacity, measured using the Gini coefficient. Evaluation year denotes the first decade in which the effects of a shifting decision are realized in the system state; shifting decisions occur in the preceding decade.

The trajectory of feasible planting capacity clarifies these dynamics. Total remaining plantable capacity declines steadily as canopy accumulates under tightening land constraints (Fig. 3d). More importantly, the spatial distribution of that remaining capacity becomes increasingly uneven (Fig. 3f), concentrating in locations misaligned with the priorities of alternative regimes. As a result, even when substantial aggregate capacity remains available, the capacity accessible to a particular regime can be limited. In effect, cities retain the ability to plant additional trees but progressively lose the ability to reconfigure their spatial distribution under an alternative adaptation regime. Forced canopy losses from urban development further reinforce this path dependence (Fig. 3e) by altering the spatial configuration inherited at the point of a regime shift independently of the allocation rule itself. Consequently, continued canopy expansion can improve collective adaptation outcomes while moving the city further from the spatial configuration that the alternative regime would have produced. Convergence in end states, therefore, does not imply convergence in justice. Instead, as canopy budgets increase, the dominant source of divergence shifts from what is allocated to how allocation sequences constrain future adaptation options.

Patterns of outcome dissimilarity across canopy budgets make this transition explicit. Under limited budgets, justice principles generate strongly differentiated spatial configurations because each rule determines where scarce canopy is allocated first (Fig. 4). At this stage, divergence is primarily distributional because prioritization matters most when resources are scarce. As canopy budgets increase, end-state differences narrow with saturation eroding the spatial distinctiveness of alternative principles (Fig. 4). Increasing canopy budgets therefore does not eliminate differences between justice principles; rather, it shifts the dominant source of divergence from how scarce canopy is distributed (distributional justice) to how allocation sequences constrain future options (procedural justice).

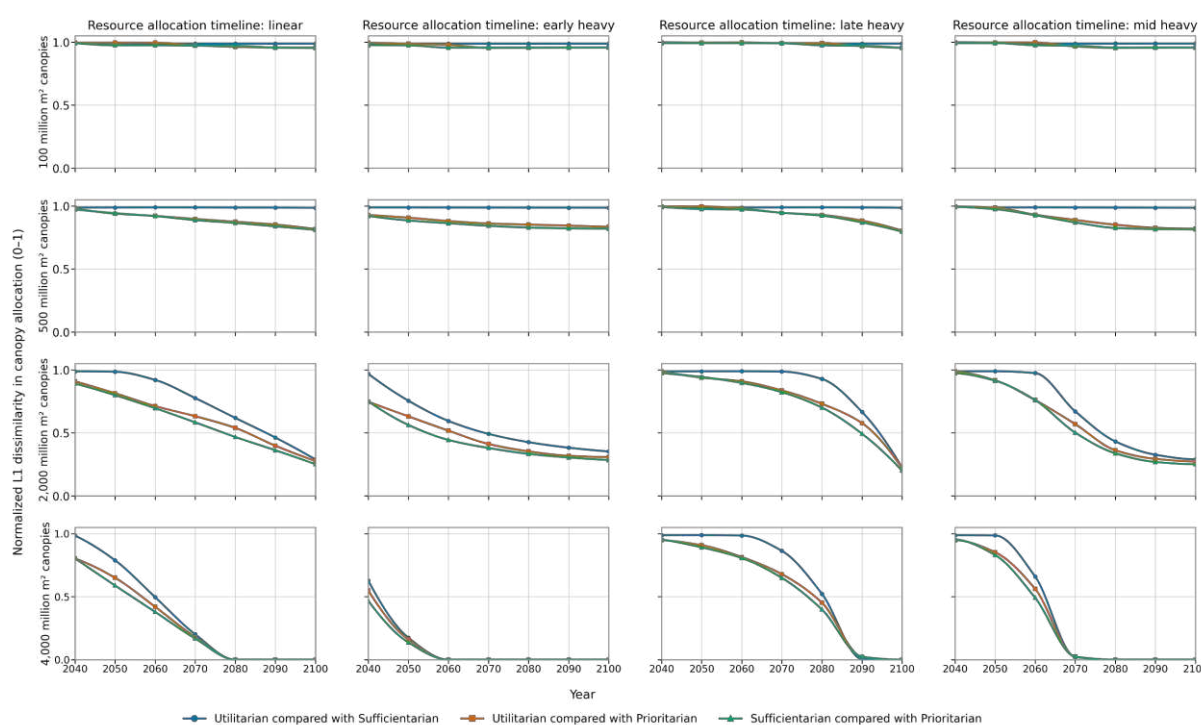


Fig. 4: Dissimilarity between justice outcomes under increasing canopy budgets under the SSP5-8.5 scenario. Pairwise normalized L1 dissimilarity between justice outcomes over time. Columns represent alternative allocation timelines (linear, early heavy, late heavy, mid heavy). Rows represent increasing total cumulative canopy budgets (100, 500, 2,000, and 4,000 million m²).

4 Discussion

Adaptation regimes can constrain future choices before they constrain future actions. Cities may lose the freedom to pursue alternative justice objectives long before they lose the physical capacity to continue adapting. Our findings show how the consequences of adaptation decisions extend beyond the benefits they deliver or the risks they reduce. By accumulating spatial commitments through time, adaptation regimes progressively shape the range of future actions that remain available to decision-makers. Across alternative justice principles, allocation timelines, climate futures, and socioeconomic pathways, the ability of successor regimes to redirect adaptation becomes increasingly constrained as commitments accumulate under

incumbent regimes. Importantly, these constraints emerge while substantial adaptation capacity remains available. The critical limitation is not whether further adaptation remains possible, but whether future decision-makers can still pursue alternative justice objectives within the inherited spatial configuration. Adaptation lock-in therefore emerges not through the exhaustion of resources, but through the progressive narrowing of feasible just adaptation regimes.

Our findings refine how flexibility is understood in urban resilience planning. In practice, keeping options open is often treated as a desirable response to uncertainty because it allows decision-makers to adjust as conditions, knowledge, and preferences change^{13,15,35}. Our results suggest that preserving future options requires more than retaining aggregate adaptation capacity. Even where substantial feasible capacity remains available, adaptation regime shifts become increasingly costly because previous allocations have already structured the decision space within which future decisions must be made. Climate adaptation should therefore be understood not only as sequences of actions leading to different outcomes, but also as processes through which spatial commitments shape the possibilities for future adaptation.

Our results also reveal how justice concerns evolve as adaptation resources expand. Under limited budgets, the primary concern is distributive, focusing on which neighborhoods receive protection first. As resources expand, the concern becomes increasingly procedural, as early commitments determine how, and for whom, future adaptation can still be redirected. Although outcomes converge at larger resource levels, this does not diminish the importance of regime choice. Instead, it relocates that importance from visible end states to the sequencing of decisions that structures future adaptation options.

The governance implications follow directly. Adaptation decisions are often made within short political cycles, while their spatial consequences persist for decades. The challenge is not simply that present governments may underinvest in long-term resilience. Rather, near-term actors can commit future administrations to a spatially structured trajectory that later actors must inherit, finance, and justify, even when they operate under different information, different social priorities, or different justice claims. Recent work on political short-termism shows how electoral incentives and immediate policy tradeoffs can bias public action toward near-term net benefits^{36,37}, while research on climate governance emphasizes that long-term strategies often fail precisely when they do not specify how future commitments will remain credible and implementable across changing political conditions³⁸⁻⁴⁰.

Under these conditions, procedural injustice in adaptation is not limited to exclusion from present decisions or unequal representation in current planning processes. It also includes the imposition of narrowed future choice sets on later publics and later governments. This is why endpoint comparisons alone are insufficient. Two regimes may converge toward similar total canopy by 2100 and yet differ profoundly in the commitments they impose along the way, the

neighborhoods protected earlier versus later, and the extent to which they preserve the possibility of revising allocation priorities as conditions evolve. The practical question for policy is therefore broader than which distribution appears more just at a given moment. It also concerns which sequencing rule most responsibly governs the transition between present and future claims.

Several implications follow for the design of adaptation governance. First, adaptation plans should be evaluated not only on projected end-state benefits but also on how early commitments align with their intended justice principles and structure future decision spaces. Second, monitoring frameworks should track how feasible capacity becomes spatially concentrated, providing early warning of how current commitments constrain the ability to pursue alternative adaptation regimes. Third, long-term heat adaptation strategies should include explicit procedural safeguards that make the timing, location, and implications of commitments transparent. Lessons from adaptive pathways practice already point to the importance of staged analysis, governance design, and learning over time⁴¹. Climate policy research similarly argues that the goal should not be rigidity around a specific instrument but stability in an overarching direction that can withstand political turnover and changing conditions^{38,39,42}. Our results suggest that, for urban heat adaptation, such stability is best achieved through well-aligned and transparent commitments that clarify the regime being pursued, rather than through attempts to defer commitment altogether.

More broadly, the case of tree canopy in Greater Sydney illustrates a general feature of urban climate adaptation. When adaptation resources are placed sequentially across space, each decision is both protective and constitutive: it reduces risk in the present while simultaneously shaping the moral and practical landscape of future action. This dual character is easy to miss when adaptation is assessed as a portfolio of projects or as a final distribution of benefits. Yet it is central to climate justice under deep uncertainty. The key question is therefore not whether cities adapt, but what kinds of future choices their current actions make easier, harder, or no longer possible. From this perspective, the most consequential adaptation decisions may be those that appear ordinary in the short-term: where trees are planted first, which neighborhoods are prioritized before others, and how rapidly a city commits its finite feasible space under one rule rather than another. By making those commitments visible and measurable, justice in urban heat adaptation emerges not only from outcomes, but from how current decision-makers govern the options available to those who come after them.

These findings should be interpreted in light of several limitations. Feasibility is represented using a stylized constraint in which building footprint defines a hard barrier to canopy expansion, abstracting from finer-grained constraints such as land ownership, land-use heterogeneity, and implementation frictions. Justice principles are operationalized through spatial allocation rules while holding governance dynamics, stakeholder preferences, and political feasibility constant. Uncertainty is represented through SSP–RCP scenarios and

projected urban expansion but does not capture all potential climate extremes or socioeconomic disruption. Finally, outcomes are evaluated using canopy-based distributional metrics rather than direct measures of heterogeneous exposure, vulnerability, or realized thermal conditions.

Future research should incorporate more detailed representations of land-use change, governance, and implementation dynamics to better capture how adaptation constraints emerge over time. Extending the framework across diverse urban and climatic contexts, and integrating participatory and agent-based approaches, would help assess the generality of the findings and examine how procedural commitments interact with broader adaptation portfolios.

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6 Methods

6.1 Study area and datasets

We defined the study area as the Greater Sydney region in New South Wales, Australia, covering all locations for which consistent data were available across tree canopy cover, building footprints, land cover, urban land development projections, and climate projections (Extended Data Fig 1a). The spatial extent was therefore determined by overlap in data coverage rather than by administrative boundaries. To integrate datasets with different native resolutions and formats, we represented the study area as a uniform grid of hexagonal microcells (Extended Data Fig 1b). We used the H3 hierarchical spatial indexing system, a geodesic discrete global grid designed for multiscale spatial analysis¹. Base-resolution H3 hexagons were obtained directly from the input datasets² and aggregated into level-1 microcells by combining each hexagon with its six adjacent neighbors using H3 parent-child relationships. This produced neighborhood-scale spatial units with an effective radius of about 75 m and a final grid of 279,965 microcells across Greater Sydney. This microcell scale was selected because it balances spatial resolution and stability. At finer resolutions, canopy and built fractions become highly sensitive to geometric variation, whereas aggregation to the microcell scale produces more robust estimates while retaining intra-urban heterogeneity. The resulting units align closely with neighborhood-scale canopy–temperature relationships reported in prior work³. All variables were treated as approximately homogeneous within each microcell.

Baseline canopy conditions were derived from the Greater Sydney Canopy Access 2022 dataset², which reports vegetation cover in an H3-compatible hexagonal grid and defines tree canopy as vegetation taller than 3 m. Canopy fraction in each microcell was calculated as the area-weighted mean across constituent base hexagons. Baseline urban land development was characterized using ESA WorldCover 2021⁴, from which the built-up class was extracted and converted into the proportion of built-up area within each microcell. Baseline building footprint was derived from the Microsoft Bing Maps open building footprints dataset⁵ by intersecting building polygons with the microcell grid and expressing their total area as a fraction of microcell area. Future urban land development projections were obtained^{6,7}, which provide decadal projections of built-up land fractions under the SSP framework. We used the 1 km downscaled projections for SSP1, SSP2 and SSP5 from 2040 onward. These projections were treated as exogenous boundary conditions and further downscaled to the microcell scale. Projected climate data were obtained from the CMIP6 application-ready datasets⁸. We used daily maximum near-surface air temperature (tasmax) under SSP1-2.6, SSP2-4.5 and SSP5-8.5, based on a multi-model ensemble of eight climate models. Values were extracted for decadal periods from 2040 to 2099, with 2099 used as a proxy for end-of-century conditions. To ensure temporal consistency, all baseline variables were indexed to 2020, and simulations were conducted at decadal decision points from 2040 to 2100.

6.2 Spatio-temporal microcell panel

We transformed the baseline microcell dataset into a spatio-temporal panel linking canopy, built form, and climate conditions across future decades. Observed baseline conditions were extended through projections that are internally consistent across space, time, and scenario. For each microcell we estimated future building footprint fractions for multiple decadal time steps under different shared socioeconomic pathways, derived from projected built-up area that is first downscaled from coarser spatial resolutions. We assigned downscaled and ensemble-averaged projections of daily maximum near-surface air temperature to each microcell for corresponding emissions pathways and target years.

6.2.1 Downscaling projected urban land development

The 1 km urban projections⁶ describe decadal changes in urban land fraction. We redistributed these changes to the approximately 75 m microcell scale while preserving, within each 1 km grid cell, the magnitude and timing of projected urban expansion. Because microcell boundaries do not align perfectly with the 1 km grid, microcells overlapping more than one 1 km cell were partitioned into sub-polygons, and all allocation steps were carried out at that piece level before being reaggregated to the full microcell.

Within each 1 km grid cell and decade, projected built-up expansion was allocated preferentially to microcells that were already more developed at the beginning of the decade. This reflected the assumption that new urban growth is more likely to occur where development is already present. Allocation was constrained by the remaining developable area within each microcell. If an initial allocation exceeded local developable capacity, the surplus was redistributed iteratively among other microcells within the same 1 km cell that still had capacity. No redistribution across 1 km cell boundaries was allowed.

This procedure ensured three properties. First, projected urban development was conserved locally up to the limit imposed by microcell-level developable area. Second, physical land constraints were respected. Third, the resulting microcell trajectories preserved the temporal structure of the 1 km SSP projections while introducing neighborhood-scale variation relevant to canopy feasibility. The full stepwise allocation algorithm, including the piece-based handling of boundary overlap and overflow redistribution, is retained for the Supplementary information - Methods.

6.2.2 Estimating future building footprint

The downscaled built-up fractions were then converted into decadal microcell trajectories of building footprint fraction under SSP1, SSP2 and SSP5. Observed building footprint in 2020 provided the initial condition. For subsequent decades, footprints were updated sequentially based on changes in built-up fraction, under the physical constraint that building footprint could not exceed total built-up land.

Where built-up land remained unchanged, building footprint was carried forward unchanged. Where built-up land declined, building footprints were contracted proportionally so that local development intensity was preserved. Where built-up land increased, the update depended on development history. If a microcell had previously exhibited non-zero building footprint, new footprint was inferred from its own prior footprint-to-built-up ratio. If built-up land increased in a microcell with no prior footprint history, local density could not be inferred directly. In such cases, we estimated footprint density using the nearest H3 neighborhood with observed footprint history, and applied a conservative default density only when no informative neighbors were found within a specified search radius.

This approach allowed future building footprints to respond to projected urban expansion while preserving consistency with local development intensity and neighborhood form. Diagnostic metadata were recorded at each decade to indicate whether each update relied on own-history density, neighborhood density, or the default rule.

6.2.3 Downscaling and ensembling climate projections

Projected daily tasmax values were assigned to microcells using centroid-based nearest-neighbor sampling from the approximately 5 km climate grid. Each microcell was represented by its centroid, and daily temperature was taken from the nearest climate grid cell. No interpolation was applied, so microcells within the same climate pixel shared the same climate signal.

This procedure was applied independently for each climate model, emissions pathway and target year. We then formed a multi-model ensemble across eight CMIP6 models and used the ensemble mean of daily tasmax. For each microcell, regime and target year, daily values were further aggregated to annual mean daily maximum temperature. These annualized microcell-level values were used in the prioritarian allocation rule to rank heat exposure.

6.3 Adaptation regime design

We designed the regime framework to separate exogenous future conditions from endogenous procedural choices. Exogenous futures were represented by three coupled SSP-RCP scenarios: SSP1-2.6, SSP2-4.5 and SSP5-8.5. These scenarios jointly shaped the evolving decision space in two ways. First, they determined urban land development trajectories, which translated into projected building footprints and therefore constrained feasible canopy expansion. Second, they determined future heat exposure, which informed priority ordering under prioritarian justice. These scenario trajectories were treated as external conditions rather than policy choices.

Within each exogenous future, adaptation regimes were defined by two procedural dimensions: justice principle and allocation timeline. We considered three justice principles, utilitarian, sufficientarian and prioritarian, and four allocation timelines, linear, early-heavy, mid-heavy and late-heavy (Extended Data Fig 2). Timelines determined when a fixed total canopy budget became available across the planning horizon, whereas justice principles determined where that

budget was allocated within each decade. This separation allowed us to examine timing and normative prioritization independently.

Total cumulative canopy budget by 2100 was varied from 25 million to 4 billion m². For a given timeline shape, changing total budget scaled the amount of canopy allocated in each decade without changing the temporal pattern of allocation (Extended Data Fig 2a). This allowed us to assess whether adaptation lock-in persisted under both scarcity and relative abundance.

Each model run was defined by a unique combination of SSP-RCP scenario, justice principle, allocation timeline and total canopy budget. Starting from observed canopy conditions in 2020, system states were updated sequentially at decadal decision points from 2040 to 2100 (Extended Data Fig 2b). At the start of each decade, future building footprint and land-use-specific canopy limits were used to update feasible canopy bounds and apply any forced canopy loss. The decade-specific canopy budget was then allocated according to the selected justice principle.

6.4 Operationalization of justice theories

All three justice principles operated on the same spatial units, state variables and feasibility constraints, and differed only in the rule used to prioritize allocations across microcells. Canopy allocation was constrained by both available non-built land and land-use-specific structural limits derived from baseline conditions. If existing canopy exceeded updated feasible bounds due to built expansion, canopy was reduced prior to allocation, and all subsequent allocations respected remaining feasible capacity.

Under the utilitarian principle, canopy was allocated to maximize aggregate cooling benefit. To quantify relative marginal cooling gains, we reproduced the neighborhood-scale canopy-temperature response³, using the 90 m partial effect as an empirical nonlinear response function. Because this function was used only to rank relative cooling gains rather than to predict absolute temperatures in Sydney, we treated it as a transferable shape rather than a transferable magnitude. For numerical stability, the response was approximated with a low-dimensional polynomial and converted to a monotone non-increasing envelope before optimization. Microcells were then ranked by marginal cooling efficiency, defined as expected cooling gain per unit canopy area, and canopy was allocated greedily from highest to lowest efficiency until the decade-specific budget was exhausted.

Under the sufficientarian principle, canopy was allocated to progressively reduce shortfall among the lowest-canopy microcells first, consistent with a threshold-oriented interpretation of the 3-30-300 rule^{9,10}. Rather than imposing a fixed 30% target directly, we used a progressive filling rule in which each decade's budget was used to raise low-canopy microcells toward a common endogenous canopy level subject to the feasibility^{11,12}. The target level was determined separately at each decade so that available canopy budget was fully used whenever feasible capacity remained.

Under the prioritarian principle, canopy was allocated first to the hottest microcells, where “worse off” was defined by projected annual mean daily maximum temperature. Microcells were ranked in descending order of heat exposure and grouped into approximately equal heat bands. Bands were filled in order, with canopy allocated uniformly within a band until either all microcells in that band reached feasible capacity or the remaining budget was exhausted.

6.5 Regime shift and lock-in analysis

We conceptualized lock-in as the cumulative divergence that remains when the system shifts from one procedural adaptation regime to another after some decisions have already been taken. To identify this effect, we conducted controlled regime shift experiments across combinations of justice principles and allocation timelines.

For each experiment, we simulated three trajectories under the same SSP-RCP scenario and total canopy budget. The first was a baseline no-shift, in which one adaptation regime governed all decisions from 2040 to 2100. The second was a target no-shift counterfactual, in which an alternative regime was followed from the outset. The third was a shifted regime, in which the system followed the baseline regime up to a selected shifting year and then adopted the target regime thereafter. Regime shift was evaluated at decadal decision points from 2040 to 2090. At the moment of shifting, previous allocations were treated as sunk, and only the remaining canopy budget was replanned over the remaining decades according to the target timeline and justice principle.

Our primary lock-in metric measured the cumulative divergence between the shifted regime and its corresponding target no-shift counterfactual, evaluated for each system state metric considered. This allows lock-in to be evaluated consistently across all regime shifts, canopy budgets, and SSP–RCP scenarios. The framework is not tied to a specific definition of system state, but operates on any scalar trajectory that summarizes the evolving condition of the system over time. In the main analysis, we report results using canopy state evenness, which captures the spatial distribution of canopy across microcells. To assess whether the observed dynamics depend on this choice, we repeat the analysis using an alternative metric, built-weighted canopy state evenness, which evaluates canopy provision relative to built area where population is typically concentrated. These metrics are illustrative rather than exhaustive. Other formulations, including those based on remaining capacity or heat resilience, can be substituted without altering the structure of the regime shift experiments or the definition of lock-in cost.

To interpret the sources of divergence, we complemented this cumulative measure with three diagnostic analyses. First, we quantified premature commitment, that is, the extent to which canopy had already been allocated to locations that the target regime would not have prioritized before the shift. Second, we quantified regime shift irreversibility at 2100 as the final spatial mismatch between shifted and target canopy distributions. Third, we quantified the unattainable shortfall at 2100, isolating the portion of the target shortfall that could not be corrected even if

all remaining feasible capacity under the shifted regime were fully used. Together, these diagnostics distinguish divergence caused by inherited spatial commitments from divergence caused by hard feasibility limits.

We also tracked how the decision space evolved through time. For each decade and regime, we quantified remaining feasible canopy capacity, forced canopy losses induced by built expansion, and the spatial concentration of remaining capacity. These measures were not themselves lock-in metrics, but they described the conditions under which lock-in emerged. In particular, they showed whether later decision makers were constrained because total capacity had shrunk, because previously established canopy had been removed, or because remaining opportunities had become increasingly concentrated in a limited subset of microcells.

7 Data availability

The publicly available datasets used in this study are described in the Methods and can be obtained from the original data providers cited therein. The processed datasets used as inputs to the Python analyses were derived from these publicly available data using the preprocessing workflow described in the Methods. The processed datasets are archived in the accompanying GitHub and Zenodo repositories. The ArcGIS Pro project used to prepare the processed datasets is available from the corresponding author upon reasonable request. The repositories will be made publicly available upon publication.

8 Code availability

The Python scripts used to generate all analyses and figures are archived in a GitHub repository together with the processed datasets required to reproduce the study. Large processed datasets are provided through an associated Zenodo repository and should be placed in the corresponding Data directories of the GitHub repository before running the scripts. The repositories will be made publicly available upon publication. During peer review, the code and processed datasets are available from the corresponding author upon reasonable request.

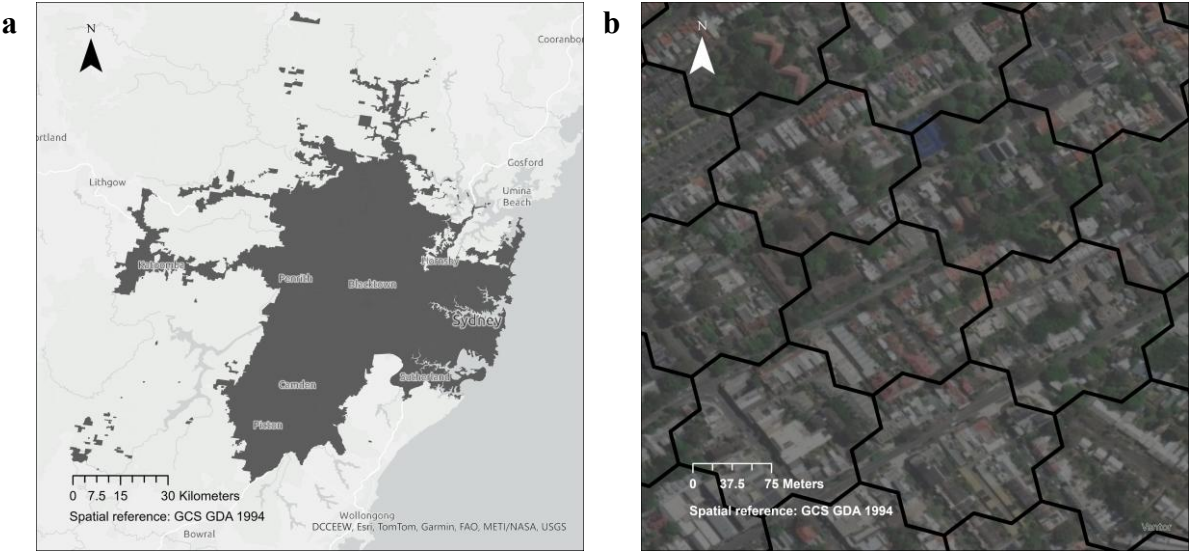
9 Additional information

Supplementary information. This manuscript is accompanied by Supplementary Information containing detailed methods and extended data figures.

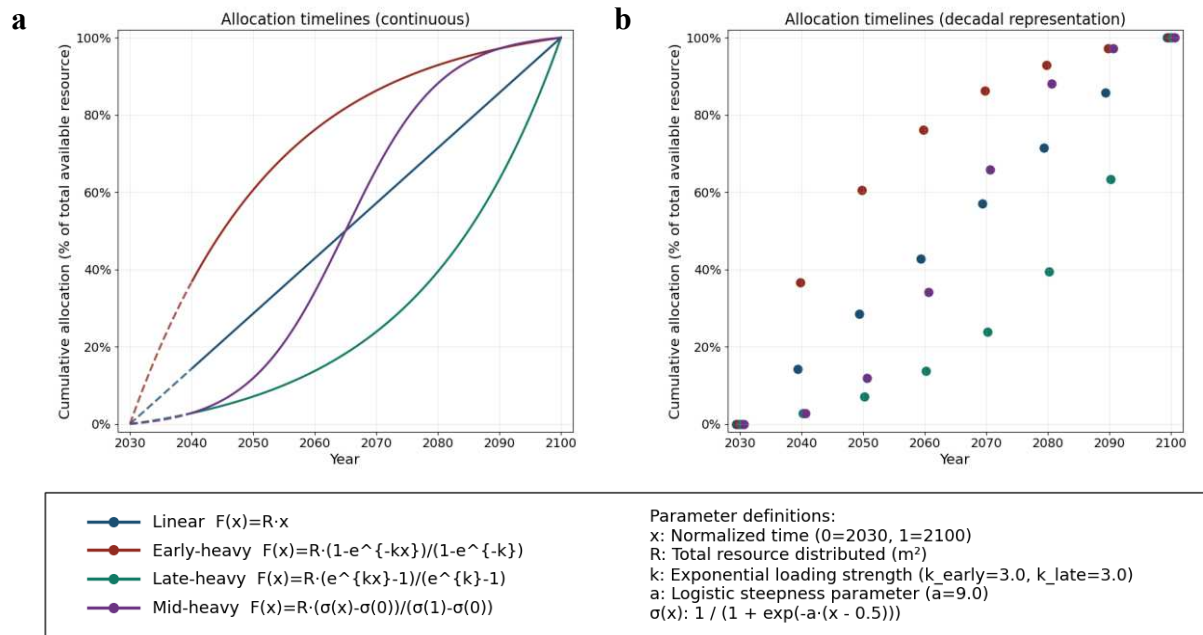
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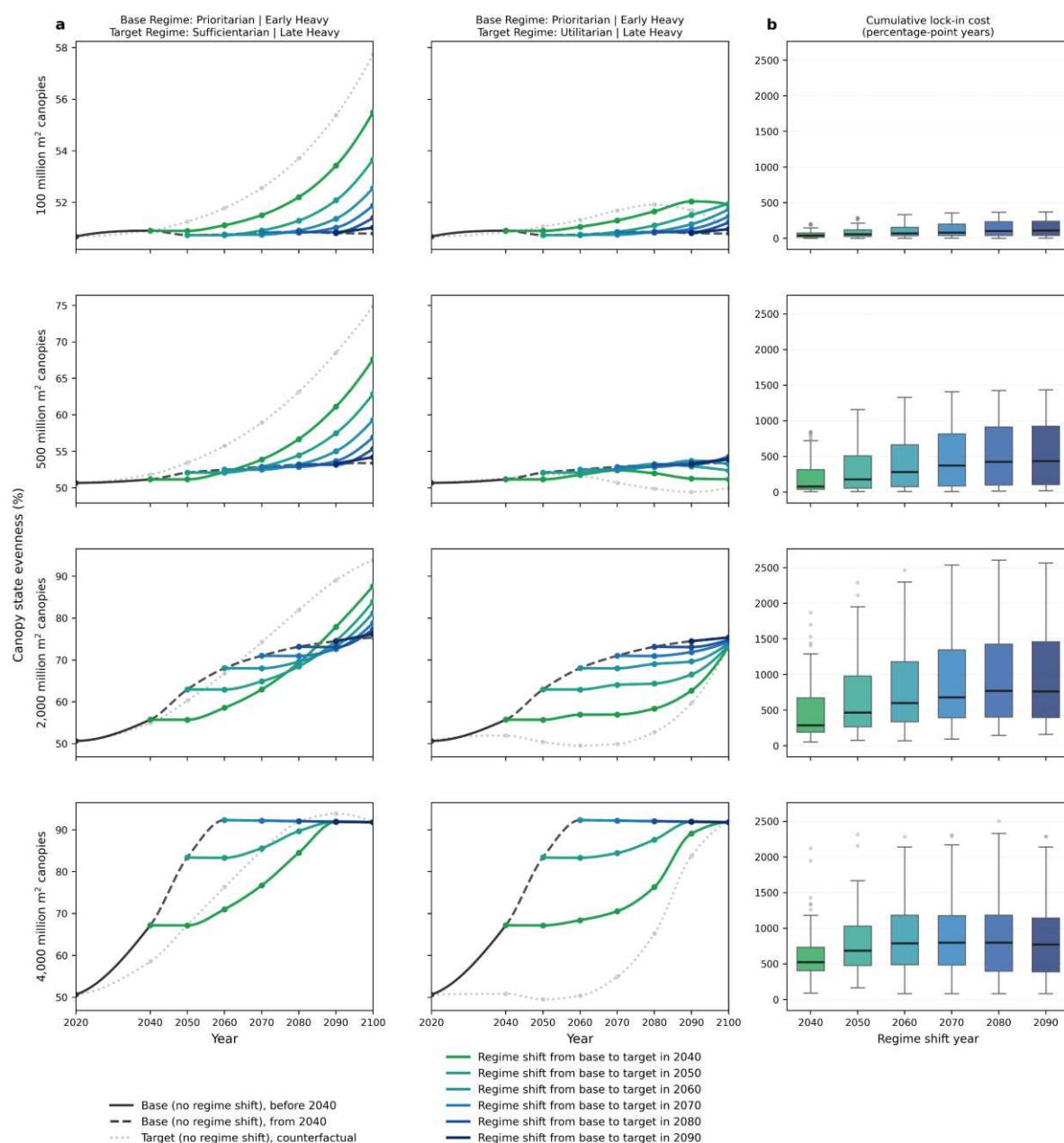
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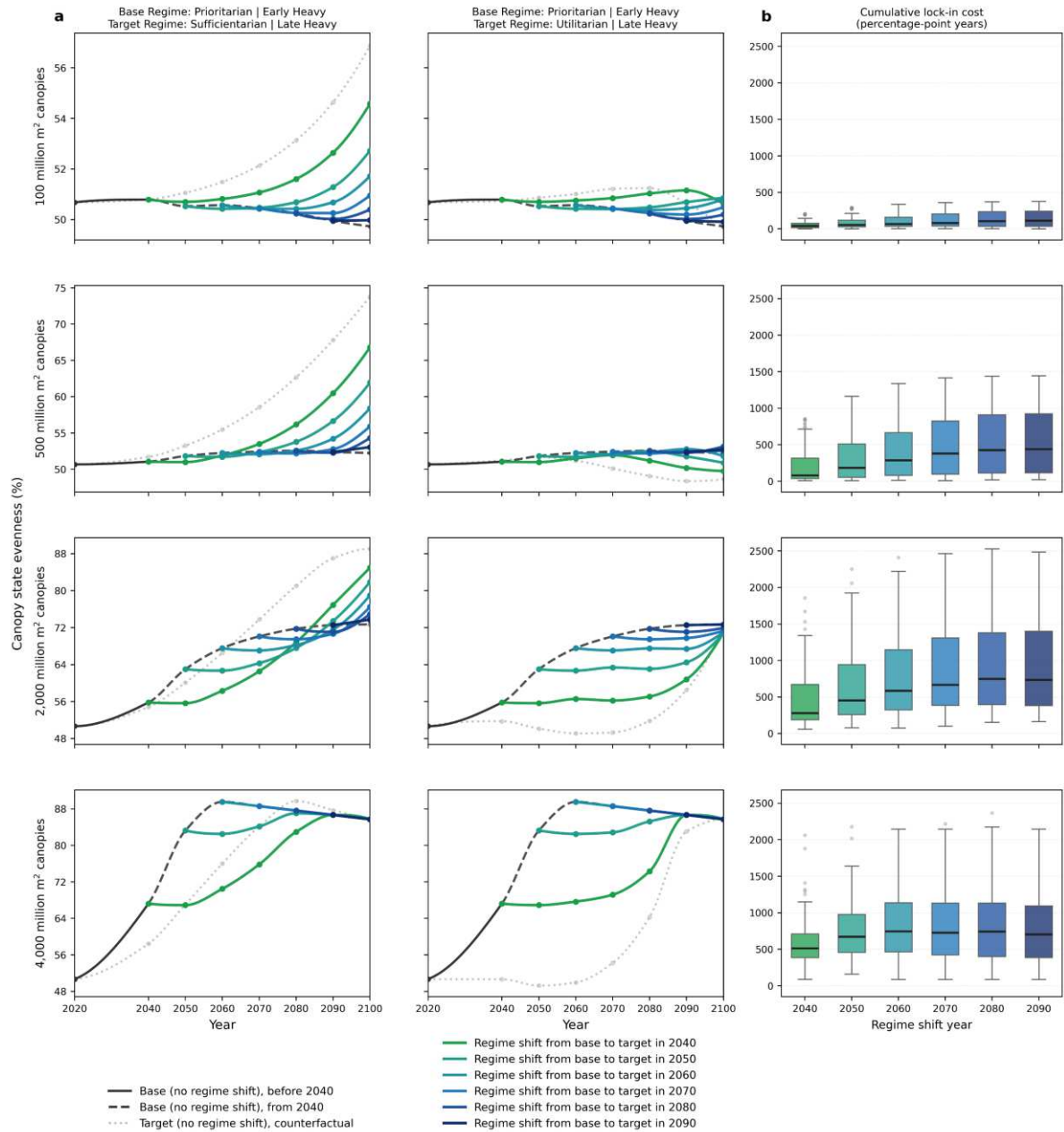
Extended Data Fig 1: Study extent and unit of analysis. a, Spatial extent of Greater Sydney, defined by the availability of consistent secondary datasets. **b,** Level-1 hexagonal microcells with an effective radius of approximately 75 m covering the analyzed extent, comprising 279,965 units.



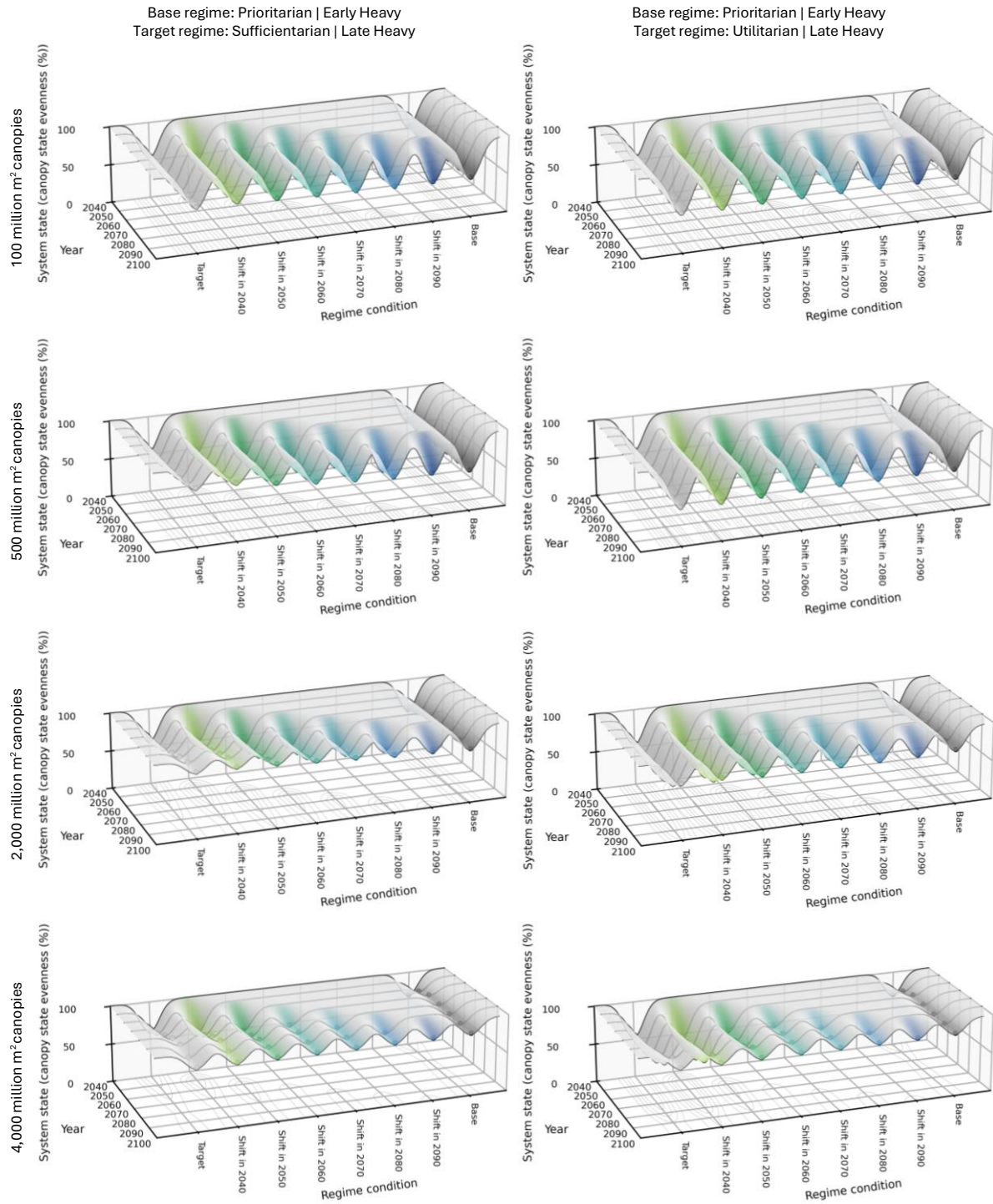
Extended Data Fig 2: Cumulative temporal allocation timelines showing linear, early-heavy, late-heavy, and mid-heavy allocation profiles. a, Continuous allocation functions over time, with dashed segments indicating the pre-2040 period and solid segments indicating allocations from 2040 onward. **b,** Cumulative allocations evaluated at decadal decision points.



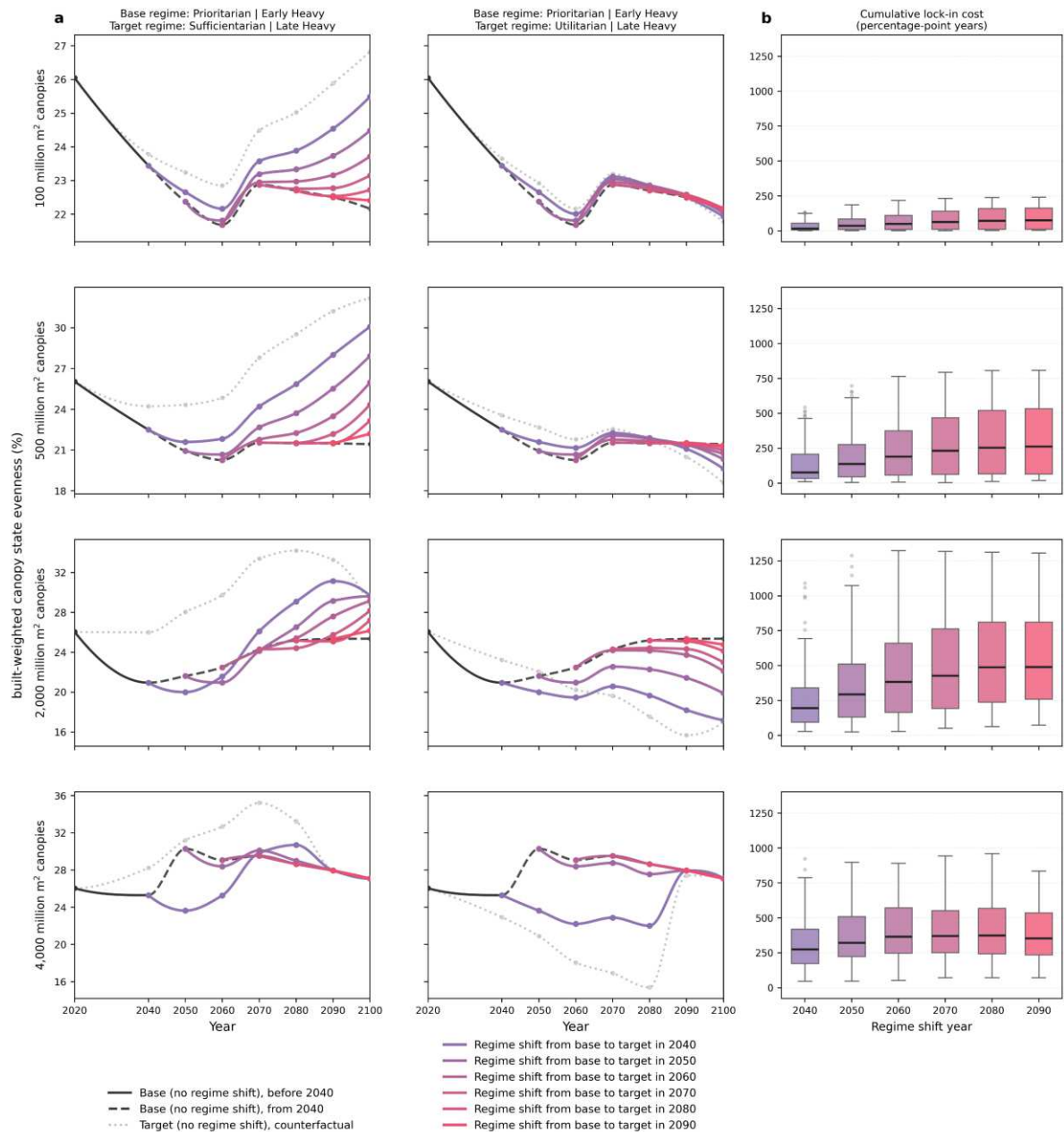
Extended Data Fig 3: Lock-in dynamics in sequential just adaptation regimes under the SSP1-2.6 scenario. **a**, Two examples of regime shift cases drawn from the full set of 132 possible shifts among 12 adaptation regimes (three justice principles $\times$ four allocation timelines; 12×11 possible base–target shifts). Branching trajectories show canopy state evenness (%), defined as $100 \times (1 - \text{Gini})$ of canopy area across neighborhood-scale microcells, under a baseline regime and alternative target regimes. Rows show increasing total canopy budgets by 2100. **b**, Distribution of cumulative lock-in costs associated with delayed shifts across all regimes. Lock-in cost is measured as the integrated area between the realized trajectory (baseline followed by the shift) and the corresponding target counterfactual trajectory from 2020–2100, expressed in percentage-point years.



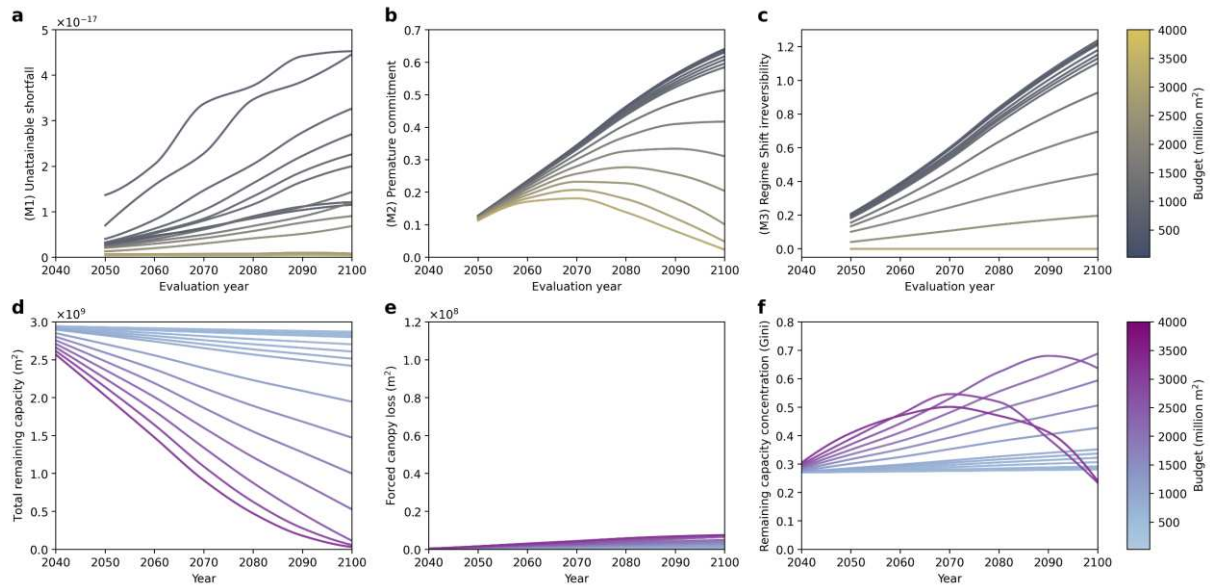
Extended Data Fig 4: Lock-in dynamics in sequential just adaptation regimes under the SSP2-4.5 scenario. **a**, Two examples of regime shift cases drawn from the full set of 132 possible shifts among 12 adaptation regimes (three justice principles $\times$ four allocation timelines; 12×11 possible base–target shifts). Branching trajectories show canopy state evenness (%), defined as $100 \times (1 - \text{Gini})$ of canopy area across neighborhood-scale microcells, under a baseline regime and alternative target regimes. Rows show increasing total canopy budgets by 2100. **b**, Distribution of cumulative lock-in costs associated with delayed shifts across all regimes. Lock-in cost is measured as the integrated area between the realized trajectory (baseline followed by the shift) and the corresponding target counterfactual trajectory from 2020–2100, expressed in percentage-point years.



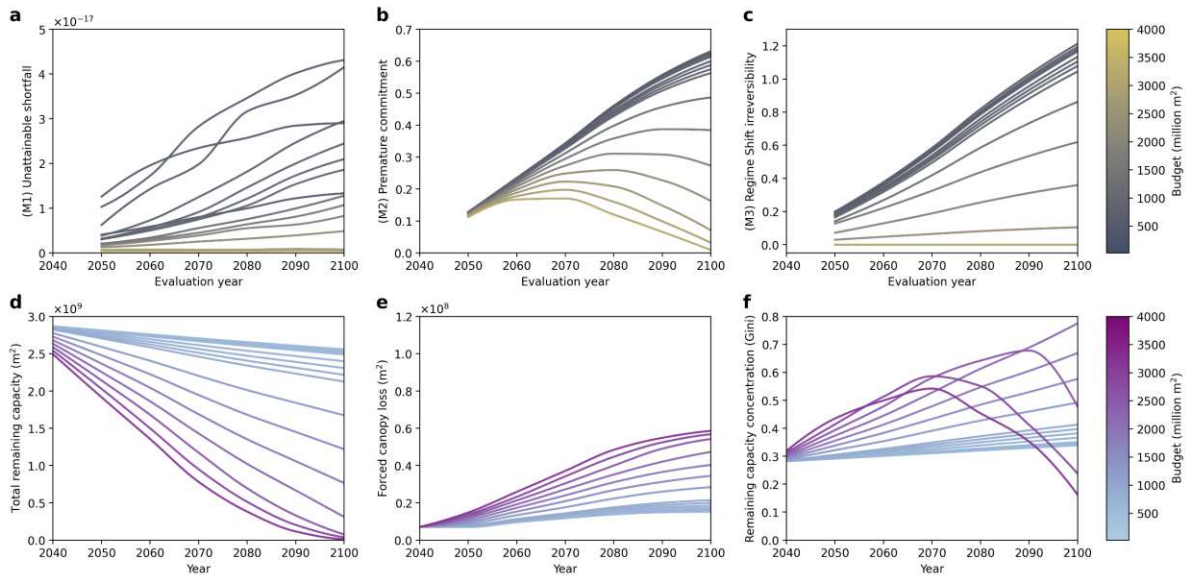
Extended Data Fig 5: State-space consequences of alternative regime-shift timings under the SSP5-8.5 scenario. Three-dimensional adaptation landscapes showing canopy state evenness (%) under two examples of regime shift cases drawn from the full set of 132 possible shifts among 12 adaptation regimes (three justice principles $\times$ four allocation timelines; 12×11 possible base–target shifts). The vertical axis represents canopy state evenness, defined as $100 \times (1 - \text{Gini})$ of canopy area across neighborhood-scale microcells. The regime condition axis represents the baseline regime, target regime, and alternative regime-shift timings between 2040 and 2090, while the temporal axis shows system evolution from 2040 to 2100. Rows show increasing total canopy budgets by 2100.



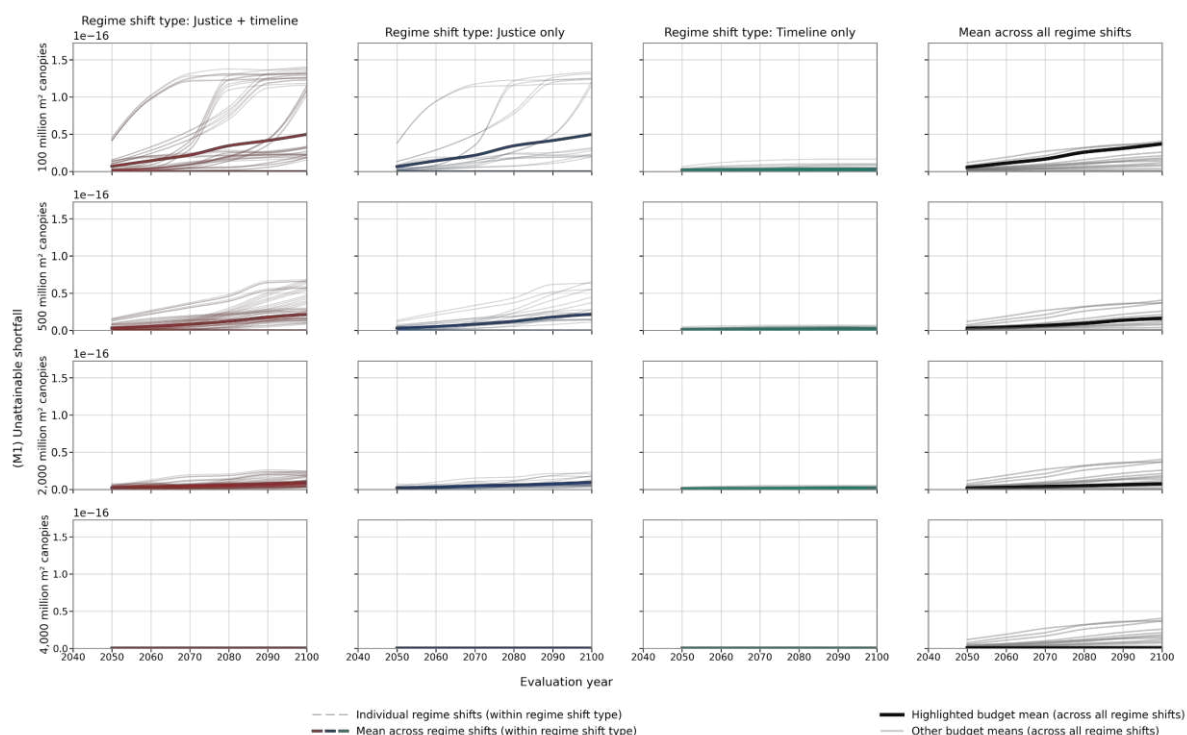
Extended Data Fig 6: Lock-in dynamics in sequential just adaptation regimes under the SSP5-8.5 scenario using built-weighted canopy state evenness metric. a, Two examples of regime shift cases drawn from the full set of 132 possible shifts among 12 adaptation regimes (three justice principles $\times$ four allocation timelines; 12×11 possible base–target shifts). Branching trajectories show built-weighted canopy state evenness (%), defined as $100 \times (1 - \text{Gini})$ of canopy provision per unit of built area across neighborhood-scale microcells, under a baseline regime and alternative target regimes. Rows show increasing total canopy budgets by 2100. **b,** Distribution of cumulative lock-in costs associated with delayed shifts across all regimes. Lock-in cost is measured as the integrated area between the realized trajectory (baseline followed by the shift) and the corresponding target counterfactual trajectory from 2020–2100, expressed in percentage-point years.



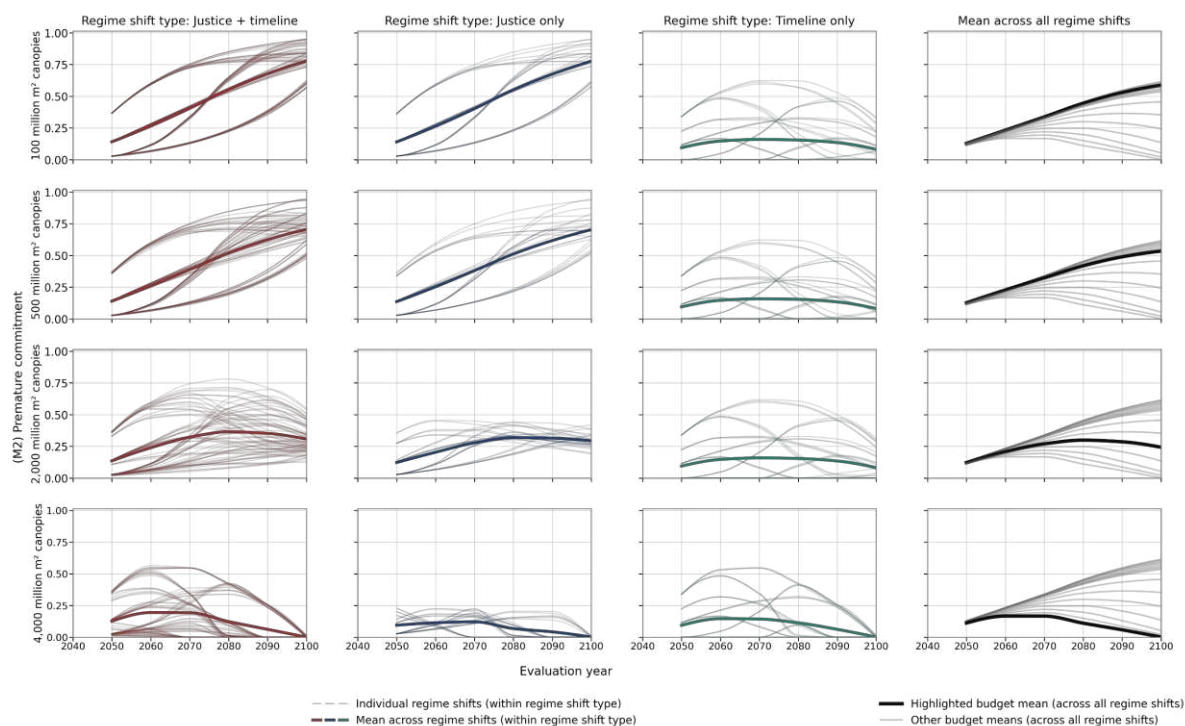
Extended Data Fig 7: Lock-in diagnostics and decision space contraction across canopy budgets under the SSP1-2.6 scenario. **a**, Unattainable shortfall shows the portion of the target canopy distribution at 2100 that cannot be recovered even if all remaining feasible capacity were used. **b**, Premature commitment shows canopy area already allocated before the shift in locations that the target regime would not have prioritized. **c**, Regime shift irreversibility shows the normalized L1 distance at 2100 between the shifted trajectory and the counterfactual trajectory that follows the target regime from 2040. **d**, Total remaining feasible canopy capacity across microcells. **e**, Forced canopy loss resulting from tightening feasibility constraints due to urban development. **f**, Spatial concentration of remaining feasible capacity, measured using the Gini coefficient. Evaluation year denotes the first decade in which the effects of a shifting decision are realized in the system state; shifting decisions occur in the preceding decade.



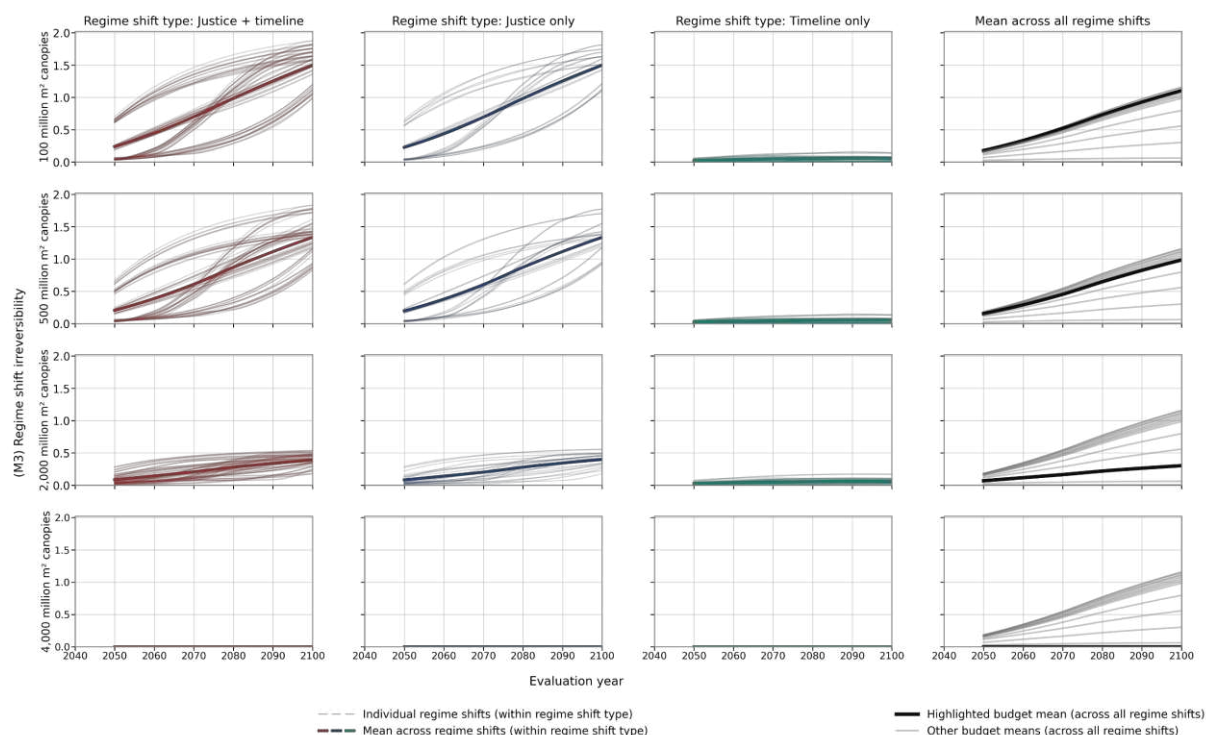
Extended Data Fig 8: Lock-in diagnostics and decision space contraction across canopy budgets under the SSP2-4.5 scenario. **a**, Unattainable shortfall shows the portion of the target canopy distribution at 2100 that cannot be recovered even if all remaining feasible capacity were used. **b**, Premature commitment shows canopy area already allocated before the shift in locations that the target regime would not have prioritized. **c**, Regime shift irreversibility shows the normalized L1 distance at 2100 between the shifted trajectory and the counterfactual trajectory that follows the target regime from 2040. **d**, Total remaining feasible canopy capacity across microcells. **e**, Forced canopy loss resulting from tightening feasibility constraints due to urban development. **f**, Spatial concentration of remaining feasible capacity, measured using the Gini coefficient. Evaluation year denotes the first decade in which the effects of a shifting decision are realized in the system state; shifting decisions occur in the preceding decade.



Extended Data Fig 9: Unattainable shortfall across shifts between adaptation regimes under the SSP5-8.5 scenario. Each curve shows unattainable shortfall for an individual shift between adaptation regimes, occurring at each shifting year (2040–2090) and evaluated one decade later. Values quantify the portion of the target allocation that remains unattainable after shifting, expressed as a normalized gap relative to the counterfactual regime, where higher values indicate larger unmet allocation. Rows indicate representative total canopy budgets, and columns distinguish shifts that change both justice principle and allocation timeline, justice principle only, or allocation timeline only, with a fourth column showing budget-level means.



Extended Data Fig 10: Premature commitment across shifts between adaptation regimes under the SSP5-8.5 scenario. Each curve shows premature commitment for an individual shift between adaptation regimes, occurring at each shifting year (2040–2090) and evaluated one decade later. Values quantify the extent of allocation committed before shifting that cannot be reallocated under the target regime, expressed as a normalized measure of early placement, where higher values indicate greater lock-in of prior decisions. Rows indicate representative total canopy budgets, and columns distinguish shifts that change both justice principle and allocation timeline, justice principle only, or allocation timeline only, with a fourth column showing budget-level means.



Extended Data Fig 11: Regime shift irreversibility across shifts between adaptation regimes under the SSP5-8.5 scenario. Each curve shows regime shift irreversibility for an individual shift between adaptation regimes, occurring at each shifting year (2040–2090) and evaluated one decade later. Values quantify the magnitude of irreversible divergence from the counterfactual regime, expressed as the residual gap in allocation outcomes. Rows indicate representative total canopy budgets, and columns distinguish shifts that change both justice principle and allocation timeline, justice principle only, or allocation timeline only, with a fourth column showing budget-level means.

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