Procedural Justice Decisions Create Lock-ins in Climate Adaptation Projects

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Abstract

Urban heat resilience is increasingly framed as a question of justice, yet most empirical studies evaluate justice at a single point in time, overlooking how adaptation decisions accumulate and become difficult to reverse. Here, we examine urban heat justice as a long-horizon decision problem structured by sequential choices, path dependence, and irreversible commitments. Using tree canopy allocation in Greater Sydney, we operationalize utilitarian, sufficientarian, and prioritarian justice principles under multiple climate and socio-economic futures and alternative investment pathways. We show that justice outcomes are strongly shaped by the timing and sequencing of decisions, not only by the total resources available. Under higher investment, distributive differences between justice principles narrow, yet outcomes become more sensitive to procedural choices that lock cities into particular trajectories. This shift does not mean that distributional justice becomes less important; rather, the ethical stakes move from visible differences in who receives resources to earlier procedural choices about which futures are made possible, delayed, or foreclosed. These findings reframe climate justice as a problem of irreversible decision making, highlighting the ethical importance of early procedural choices in shaping long-term protection and exposure.

1 Research Problem

Urban heat is an increasingly severe and unequal climate risk, shaped by both global warming and long-standing patterns of urban development (Anguelovski et al., 2022; Hsu et al., 2021; Tuholske et al., 2021). Heat exposure varies sharply within cities, reflecting differences in land cover, building density, and socio-economic conditions, and these differences translate into unequal health, productivity, and livability impacts (Li et al., 2025; Masselot et al., 2023; Stechemesser & Wenz, 2023). As a result, heat resilience projects are increasingly framed not only as a technical or public health challenge, but also as a question of justice (García-Lamarca et al., 2022; Strange et al., 2024; Walker et al., 2024). Decisions about where, when, and how heat resilience resources are deployed determine who benefits from protection, who remains exposed, and how risks evolve over time (Haasnoot et al., 2013; Werners et al., 2021).

Much of the existing literature on justice in heat resilience focuses on distributional outcomes at a single point in time, often asking whether resources are allocated equitably across neighborhoods or social groups (Hsu et al., 2021; Mitchell & Chakraborty, 2014; Pakizeh et al., 2026). However, resilience in practice is rarely a one-off allocation problem (Meerow et al., 2016; Tyler & Moench, 2012). Instead, it unfolds incrementally over decades, under uncertainty about future climate conditions, patterns of urban development, and available resources (Haasnoot et al., 2013; Hallegatte, 2009; Seto et al., 2012). Early decisions shape later possibilities, progressively constraining what remains feasible (Wise et al., 2014). As adaptation investments accumulate, some options are preserved while others become increasingly difficult to pursue. This process creates path dependencies, whereby earlier decisions influence the set of choices available in later periods. Over time, these path dependencies can generate lock-ins, as previous allocations, development trajectories, and planning assumptions progressively narrow the range of feasible future adaptation strategies. Under such conditions, irreversibility emerges not because change becomes impossible, but because altering earlier commitments becomes increasingly costly, constrained, or impractical. Justice therefore becomes not only a matter of how outcomes are distributed, but also of how decisions are sequenced, which assumptions guide planning, and which futures remain possible or become foreclosed (Tschakert et al., 2017; Walker, 2012).

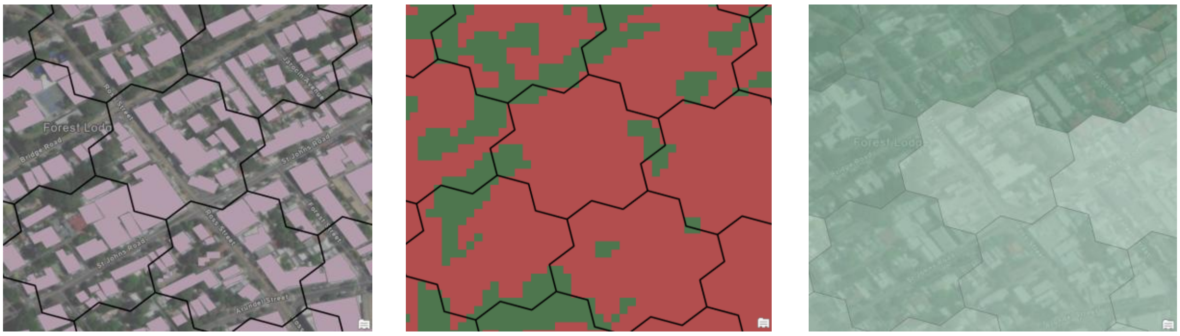
In this study, we examine justice in urban heat adaptation as a long-horizon decision problem shaped by sequential choices, path dependence, and irreversible commitments. Using tree canopy allocation in Greater Sydney as an empirical case, we operationalize three widely used theories of justice, including utilitarian, sufficientarian, and prioritarian, and examine how they perform when adaptation decisions are made sequentially, under multiple Shared Socio-economic Pathways (SSPs), Representative Concentration Pathways (RCPs) and alternative investment pathways. By tracing how justice outcomes evolve as resources accumulate and earlier decisions commit systems to particular trajectories, the analysis moves beyond endpoint comparisons to reveal how procedural choices condition the feasibility of later allocations. This perspective allows justice to be evaluated not only in terms of who benefits, but in terms of when protection is delivered, which options are preserved or foreclosed, and how irreversibility reshapes the ethical stakes of heat resilience planning. Although the empirical analysis focuses on Greater Sydney, the argument applies more broadly to cities where adaptation resources are allocated incrementally under land-use constraints, climate uncertainty, and long-term planning commitments.

2 Research Methodology

The analysis is conducted at a granular spatial resolution using micro-scale spatial units, referred to here as microcells, that capture the scale at which heat exposure, land-use constraints, and planning decisions interact. The study area covers Greater Sydney, a large and diverse metropolitan region facing increasing heat risk under climate change and ongoing urban development.

2.1 Spatial Framework and Data Preparation

The urban region is discretized into a uniform grid of level-1 hexagonal microcells, each representing a fine-scale spatial unit with an effective radius of approximately 75 m, within which land cover, built form, and climate exposure are assumed to be relatively homogeneous (Figure 1). For each microcell, we compile a comprehensive dataset including existing tree canopy cover and building footprints. Building footprint data are used to estimate the maximum feasible tree canopy that can be added within each microcell, defining a hard upper bound on allocation and ensuring that modeled adaptation remains physically plausible under planning and space constraints.



(a) (b) (c)

Figure 1. Level-1 hexagonal microcell units with an effective radius of 75 m covering the Greater Sydney region. (a), building footprints (%) in the base year (2020). (b), urban land development (%) in the base year (2020). (c), tree canopy coverage in the base year (2020).

Climate exposure is represented using daily maximum air temperature, reflecting the metric most closely associated with heat-related health risks. Future temperatures are derived from application-ready CMIP6 datasets produced by the Australian Climate Service and the NSW Government's NARCliM2.0 project, based on an ensemble of eight climate models under SSP–RCP 1-2.6, 2-4.5, and 5-8.5 scenarios (Climate Change in Australia, 2025). The data are provided as daily values on an approximately 5 km grid for decadal periods from 2040 to 2100, generated using a scaling approach that applies quantile-based changes from CMIP6 models to high-quality gridded observational and reanalysis datasets from the Bureau of Meteorology. Climate projections are downscaled to the microcell level using nearest-neighbor assignment, whereby each microcell inherits temperature values from the grid cell containing its centroid, enabling consistent estimation of projected heat exposure across the urban region.

Urban development is incorporated via a decade-by-decade downscaling pipeline that converts SSP-consistent 1 km urban land projections (Gao & Pesaresi, 2021) into microcell-level projections of built-up. For each decade and scenario, we compute the implied urban expansion within each 1 km cell as the change in urban land fraction relative to the previous decade, then disaggregate that increment to the microcells contained in the cell using an iterative, capacity-constrained allocation. Microcells receive shares of the 1 km increment according to weights derived from their beginning-of-decade built-up condition, with any allocation that would exceed a microcell's remaining developable area treated as overflow and redistributed to other microcells within the same 1 km cell until the full increment is allocated. This produces a consistent microcell-level trajectory of projected urbanization that preserves the coarse-scale totals while allowing heterogeneous fine-scale patterns (Gao & Pesaresi, 2021).

We then translate projected urbanization into projected building footprints to impose time-varying canopy capacity constraints. For microcells with existing buildings, building footprint density is estimated from historical observations and applied forward to the projected built-up area subject to land availability. For microcells that transition from green or undeveloped to urbanized states under specific scenarios, building footprint is inferred using a neighborhood density model calibrated on historical data: the expected building footprint is predicted from the observed footprint density of the focal microcell and its local context, defined as neighboring microcells within a five-ring radius, to assign plausible built form where local history provides no analogue. The model is used as a planning constraint rather than as a deterministic forecast of future built form, and its uncertainty matters because overestimating future footprints would understate feasible canopy space, while underestimating them would overstate future protection potential. The resulting decade-specific building footprint estimates define a hard upper bound on plantable space per microcell, ensuring that canopy allocation remains feasible under projected densification and enabling joint evaluation of climate warming and evolving spatial constraints.

All datasets are harmonized spatially and temporally to ensure that each microcell is associated with a complete time series of baseline conditions, projected heat exposure, and feasible canopy capacity from 2040 through 2100.

2.2 Resource Allocation Pathways

Tree canopy is treated as a cumulative adaptation resource that is allocated incrementally over time (Figure 2). Rather than assuming a single investment profile, we define four distinct resource investment pathways that describe how the total available canopy is deployed across the planning horizon: a linear pathway, an early-heavy pathway that front-loads investment, a late-heavy pathway that defers investment to later decades, and a mid-heavy pathway that concentrates allocation around mid-century. Each pathway is represented as a continuous allocation function normalized to the total available resource, enabling direct comparison across scenarios independent of absolute budget size.

Total resource availability is varied across a wide range, from low to high cumulative investment levels, allowing us to examine how justice outcomes evolve as adaptation moves from scarcity toward relative abundance. Once allocated, canopy persists in subsequent periods, reflecting the durability of greening interventions and reinforcing the sequential and path-dependent nature of adaptation decision making. This persistence is the main physical mechanism of lock-in in the model: earlier allocations occupy part of the feasible canopy capacity and therefore reduce the space of later reallocations. However, the interpretation of lock-in is broader, because investment schedules, scenario assumptions, and modelling choices also influence which options are considered feasible or desirable.

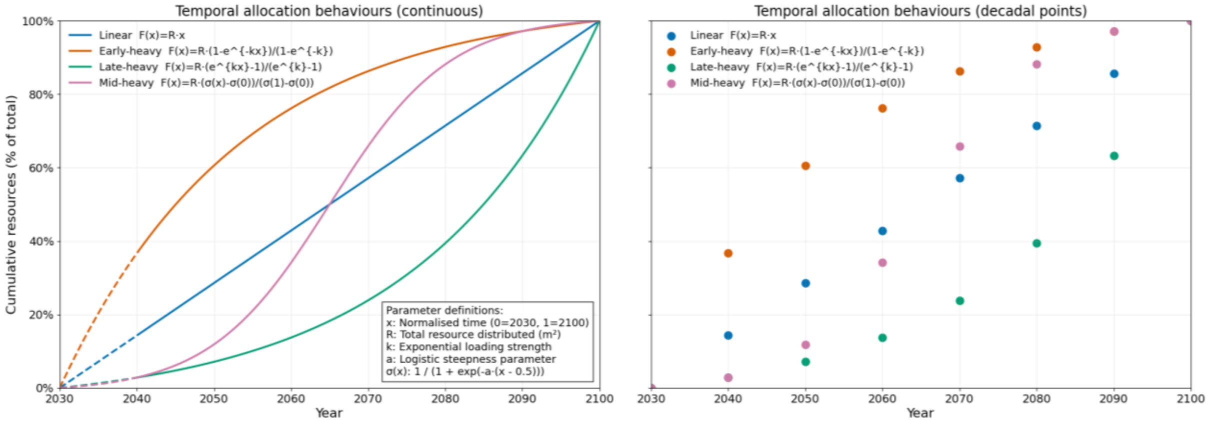


Figure 2. Temporal allocation pathways for heat adaptation resources. Cumulative resource allocation is shown as a percentage of total available resources from 2040 to 2100 under four alternative investment pathways: linear, early-heavy, late-heavy, and mid-heavy. The left panel shows continuous allocation functions over time, with dashed segments indicating the pre-2040 period and solid segments indicating allocations from 2040 onward. The right panel shows cumulative allocations evaluated at decadal decision points.

2.3 Operationalizing Justice Theories

We operationalize three widely discussed justice theories in the allocation of tree canopy: utilitarian, sufficientarian, and prioritarian. Each theory is implemented as a formal decision rule applied consistently across all scenarios and pathways.

The utilitarian approach allocates canopy to maximize aggregate heat reduction across the urban region. Cooling benefits are estimated using a nonlinear temperature–canopy response function derived from empirical literature on urban greening and heat mitigation (Ziter et al., 2019). This function captures diminishing marginal cooling returns at higher canopy levels, ensuring that allocation decisions reflect realistic biophysical behavior. Specifically, the response function captures the empirically observed nonlinear relationship between canopy cover and urban cooling reported by Ziter et al. (2019), whereby cooling benefits vary across the canopy gradient rather than increasing linearly with added canopy. As a result, the cooling benefit of an additional unit of canopy depends on existing canopy conditions within a microcell, creating heterogeneous returns across the urban landscape.

The sufficientarian approach seeks to ensure that all microcells reach a minimum acceptable level of protection. This minimum is defined using a canopy sufficiency threshold informed by urban greening benchmarks, including the widely cited 3–30–300 rule (Browning et al., 2024; Konijnendijk, 2023). Allocation prioritizes microcells below the threshold until sufficiency is achieved where feasible, after which remaining resources are distributed according to secondary criteria.

The sufficientarian approach seeks to ensure that all microcells reach a minimum acceptable level of protection, motivated by urban greening benchmarks such as the 3–30–300 rule

(Browning et al., 2024; Konijnendijk, 2023). Rather than imposing a fixed canopy threshold, canopy is allocated iteratively to microcells with the lowest initial coverage, raising them stepwise to match the next higher coverage level observed in the existing distribution. The sufficiency threshold therefore emerges endogenously from the data and increases with the total amount of available resources, potentially exceeding 30% under higher amount of resources or remaining below it when resources are constrained. This implementation avoids treating sufficiency as a single universal target and instead models it as a resource-sensitive principle: the relevant question is how far the least protected locations can be raised under the available budget and space constraints.

The prioritarian approach prioritizes microcells facing the greatest projected heat exposure. Here, future heat risk is estimated using projected daily maximum temperatures under each climate scenario, and canopy is allocated preferentially to locations expected to experience the most severe conditions. This embeds future-oriented concern for vulnerability directly into the allocation process.

All three justice theories are subject to the same physical and planning constraints, including maximum feasible canopy per microcell and the cumulative nature of investment.

2.4 Evaluating Outcomes and Sensitivity

For each combination of climate scenario, investment pathway, cumulative resource level (ranging from 25 to 4000 million square meters of canopy distributed through 2100 according to the allocation pathways shown in Figure 2), and justice theory, we compute the resulting spatial distributions of canopy cover and associated heat exposure across microcells.

To quantify how strongly justice theories diverge in their allocation outcomes, we calculate distributional distance between justice-based solutions while holding climate scenario, investment pathway, cumulative resource level, and year constant. For each such combination, we compute the mean microcell-level distance across all pairwise comparisons of justice theories using the L1-half distance metric. This yields a scalar value that captures how different the resulting spatial allocation patterns are across the urban region, independent of total canopy amount.

For a given cumulative resource level, distributional distance values are then aggregated across all climate scenarios, investment pathways, and years. The mean distance is interpreted as the "distributional importance" of justice at that resource level, reflecting how strongly normative differences between justice theories influence outcomes. To characterize variability, we also report the 10th–90th percentile range of distance values across scenarios. To enable comparison across resource levels, all distance values are normalized to the unit interval [0, 1], where 0 indicates identical allocation outcomes across justice theories and 1 represents the maximum observed divergence within the analysis.

To quantify procedural sensitivity, we assess how strongly allocation outcomes vary with changes in climate scenarios and investment pathways, holding the justice principle fixed. Rather than comparing justice theories to one another, this measure captures the dispersion of outcomes induced by scenario assumptions and sequencing choices. Procedural sensitivity therefore identifies cases where the same justice principle produces different outcomes depending on when resources are deployed, which climate future is assumed, and which urban development pathway is used.

For each cumulative resource level, we compute the interquartile range (IQR) of distributional distance values across all combinations of climate scenarios, investment pathways, and years. The IQR provides a robust measure of dispersion that is less sensitive to outliers and reflects the typical spread of outcomes attributable to procedural variation. Higher IQR values indicate that outcomes are more sensitive to scenario and pathway choices, while lower values indicate relative procedural stability. As with distributional distance, procedural sensitivity values are normalized to the unit interval [0, 1]. This normalized measure is interpreted as the "procedural importance" of justice, capturing the extent to which outcomes depend on assumptions about future climate conditions and the sequencing of investment rather than on distributive principles alone.

Evaluating distributional importance and procedural importance jointly allows us to distinguish disagreement arising from normative differences between justice theories from sensitivity arising from procedural choices. Tracking both measures across increasing cumulative resource levels reveals how justice shifts from distributional divergence under scarcity toward procedural dependence under abundance, as early decisions progressively constrain the set of feasible future outcomes. These two measures should not be read as ethically identical. Distributional importance captures disagreement over who receives protection, while procedural importance captures how planning assumptions and sequencing decisions shape future choice. When distributional differences are small but procedural sensitivity is high, the planning implication is not to ignore justice, but to prioritize robustness, transparency, and flexibility across plausible futures.

3 Key Findings

The results reveal a consistent pattern across climate scenarios, investment pathways, and cumulative resource levels. Under conditions of limited cumulative resources, different justice theories produce sharply divergent allocation outcomes. Distributional differences are substantial, and normative choices about who should be prioritized have clear and immediate consequences for which microcells receive protection and which remain exposed. Under scarcity, justice is highly contested and visibly expressed through spatial outcomes (top rows in Figure 3).

As cumulative resource investment increases, these distributional differences between justice theories decline markedly. However, this convergence does not reflect ethical agreement or the resolution of justice debates. Instead, it emerges from physical, spatial, and planning constraints that progressively saturate the feasible allocation space. As more microcells approach their maximum feasible canopy coverage, the range of meaningful allocation choices narrows. Under these conditions, different justice rules necessarily yield similar outcomes, not because their normative commitments align, but because few alternatives remain available (bottom rows in Figure 3). This is why declining distributional distance should not be interpreted as justice becoming less relevant. It may instead indicate that earlier choices have already constrained the field of possible outcomes.

At the same time, procedural sensitivity increases. As resources accumulate, outcomes become more dependent on assumptions about future climate trajectories, urban development patterns, and the timing and sequencing of investment (Figure 4). Small differences in scenario assumptions or allocation pathways can lead to substantial differences in who is protected and when, even when the same justice theory is applied. Early decisions shape the set of future options and can lock in exposure patterns that are difficult or impossible to reverse later. As cumulative investment grows, visible distributional conflicts diminish, while the stakes of procedural choices rise. Justice does not disappear with abundance; it changes form. Under scarcity, justice is contested through competing distributional outcomes. Under abundance, justice is increasingly embedded in assumptions, scenarios, and sequencing decisions that determine which futures remain feasible. This does not imply that all procedural choices are equally justice-relevant. Choices that affect the timing of protection for highly exposed areas or the preservation of future canopy capacity have greater ethical significance than choices with little effect on exposure or feasibility.

The analysis also highlights structural limits to local adaptation. While local allocation decisions can redistribute heat exposure within cities, they cannot offset the scale of residual harm under more severe climate futures, such as SSP–RCP 5–8.5, at realistic levels of adaptation investment. For example, even with an additional 50 million square meters of tree canopy deployed by 2100, substantial heat exposure persists under high-emissions scenarios (left panel of Figure 5). As a result, justice debates in adaptation increasingly concern how remaining harm is distributed under conditions shaped by global mitigation success or failure. In this sense, adaptation justice becomes inseparable from questions of responsibility for, and exposure to, residual climate risk. This finding extends beyond Greater Sydney because many cities face the same combination of local adaptation limits, constrained urban space, and dependence on global mitigation trajectories.

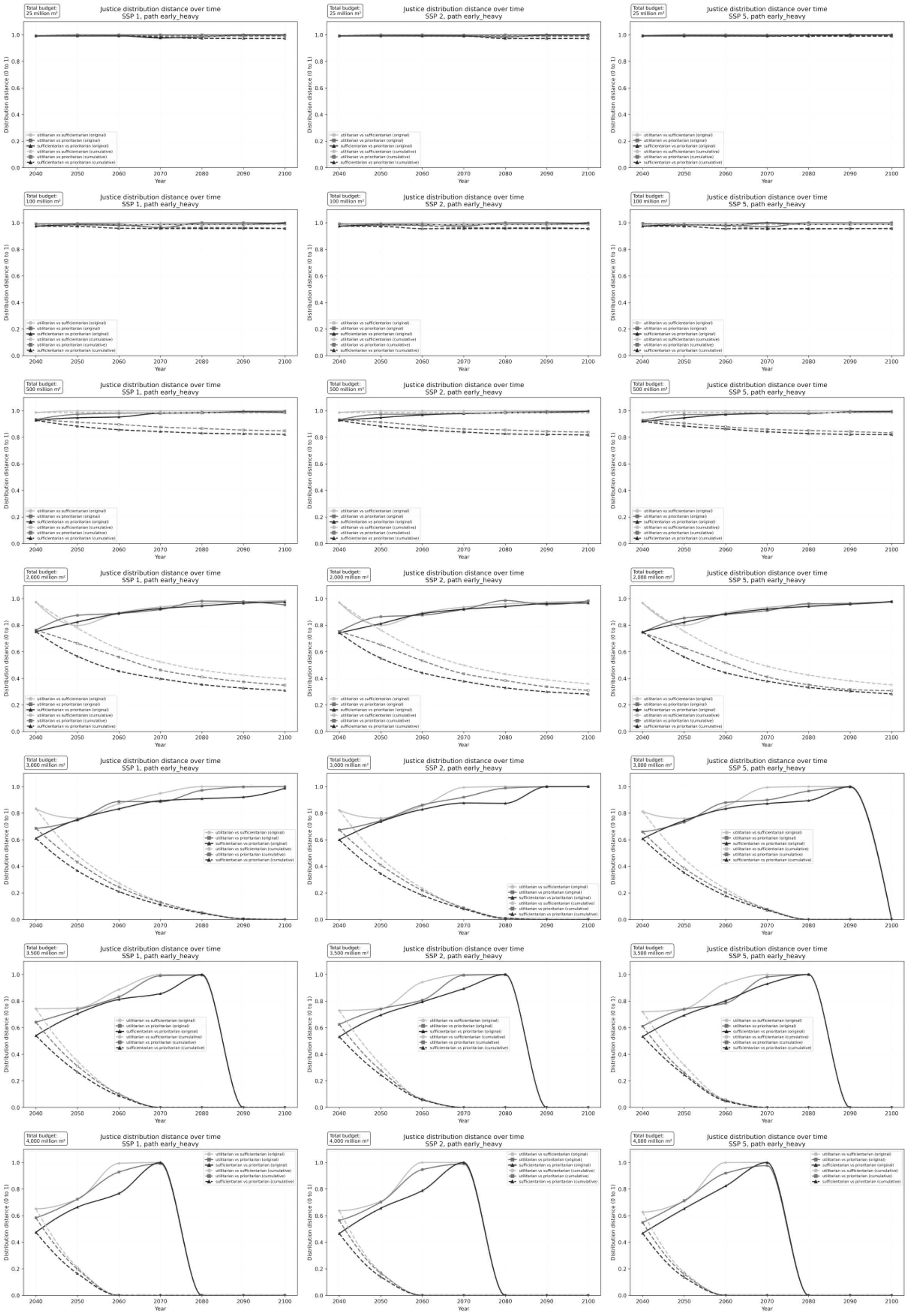


Figure 3. Pairwise distributional distances between justice-based canopy allocation outcomes under the early-heavy investment pathway. Panels show selected cumulative resource levels (25, 100, 500, 1000, 2000, 3000, 3500, and 4000 million m²), with each curve representing the distance between a pair of justice theories. Distances are computed at the microcell level and aggregated across the urban region. Panels are ordered by increasing total resource availability.

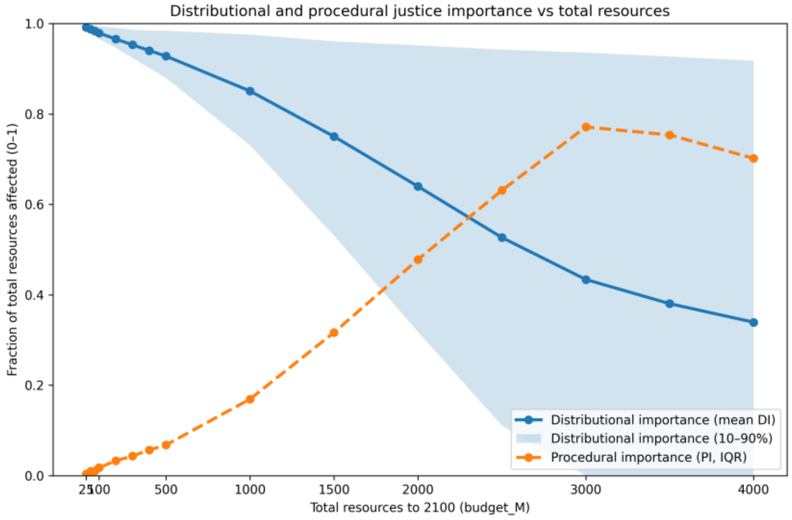


Figure 4. Distributional and procedural justice importance as a function of total adaptation resources. The solid line shows mean distributional importance across justice theories, with the shaded band indicating the 10–90th percentile range across scenarios. The dashed line shows procedural importance, quantified as the interquartile range of outcomes across climate scenarios and investment pathways. Values are normalized to the 0–1 range, indicating the fraction of total resources whose allocation is sensitive to distributive rules or procedural choices.

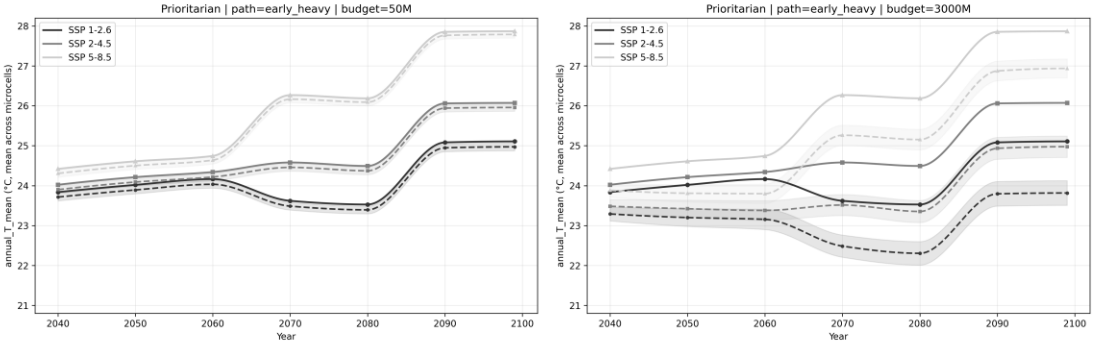


Figure 5. Projected mean annual temperature across microcells under the prioritarian allocation strategy and early-heavy investment pathway, shown for two cumulative resource levels: 50 million m^2 (left) and 3000 million m^2 (right). Solid lines show baseline temperature trajectories under SSP 1–2.6, SSP 2–4.5, and SSP 5–8.5. Dashed lines and the associated shaded bands indicate the aggregate cooling effect produced by the allocated canopy under each resource level, expressed as the reduction in mean annual temperature across the Greater Sydney region.

4 Implications

These findings reframe justice in long term climate resilience as a problem of decision design rather than merely outcome evaluation. They show that justice does not fade as resources increase, but shifts from visible distributive disagreement to less visible but more consequential procedural commitments that shape future exposure. For planning practice, this means that justice assessment should begin before resources are allocated, not only after outcomes are mapped.

First, the findings imply that procedural choices are not secondary technical inputs but primary determinants of justice in long horizon resilience. As cumulative investment increases, outcomes become less sensitive to distributional rules and more sensitive to assumptions about climate futures, sequencing of investments, and model structure. These procedural decisions shape which futures remain feasible and which exposure patterns become locked in. In practical terms, this means that scenario selection, investment pathways, and modelling assumptions should be treated as justice relevant decisions that require explicit justification, documentation, and accountability, rather than being embedded implicitly within technical analyses. Planning agencies could operationalize this by requiring adaptation plans to report why particular scenarios were selected, how investment timing affects vulnerable areas, and whether alternative pathways would preserve more future flexibility.

Second, the results highlight timing as a central justice mechanism in urban heat resilience. The point at which justice debates appear to fade is not when fairness has been achieved, but when earlier decisions have rendered alternative allocations infeasible. For affected communities, this distinction is critical because exposure to heat risk is cumulative and experienced over time. Resilience projects that prioritize eventual equity while delaying early protection may produce long lasting harm even under high total investment. This suggests that justice-oriented planning should evaluate not only final allocation outcomes, but the temporal distribution of protection and exposure across populations and areas. A practical implication is that project appraisal should include interim justice checks at each investment stage, especially where delayed protection would leave high-risk communities exposed for decades.

Finally, these findings imply a need to reframe resilience governance around irreversibility and path dependency. As adaptation decisions accumulate, they progressively restrict future choice, increasing the ethical stakes of early procedural commitments. Justice in long term climate resilience therefore shifts from visible disagreement over outcomes to less visible but harder to reverse decisions about which futures are pursued. Embedding this perspective into planning processes would support governance approaches that make procedural commitments explicit, preserve flexibility where possible, and recognise that the most consequential justice decisions may occur long before distributional outcomes converge. For other cities, the specific canopy, temperature, and development data will differ, but the governance problem is similar: adaptation pathways should be assessed for how they distribute benefits now, how they preserve future options, and how they avoid locking in avoidable exposure.

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