Understanding Green Development and Urban Displacement

Modeling Demographic Shifts, Rental Disparity, and Nature-Based Solutions in Cape Town, South Africa

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This research highlights how nature-based solutions and housing justice can contribute to SDGs 10, 11, and 13 (UN, 2015).

10 REDUCED INEQUALITIES

11 SUSTAINABLE CITIES AND COMMUNITIES

13 CLIMATE ACTION

Executive Summary

Nature-based solutions (NbS) such as urban parks, green corridors, and stormwater wetlands are increasingly adopted to enhance climate resilience and livability in cities, yet their social impacts can be uneven. In Cape Town—where apartheid-era planning left certain communities on the under-resourced Cape Flats while the wealthier people clustered around greenspaces—there is a pressing need to understand whether greening projects might inadvertently displace vulnerable renters. This thesis examines that question by focusing on two contrasting electoral wards: Ward 57, an affluent inner-city neighbourhood, and Ward 79, the lower-income Mitchell's Plain township in the Cape Flats.

To explore how NbS affect housing affordability and demographic composition, a spatially explicit agent-based model (ABM) was developed for each ward. The city map is discretized into a grid of housing parcels, each with evolving rent levels and 'livability' scores that reflect environmental quality, including the presence and maturity of NbS interventions. Household agents—characterised by income, rent-affordability thresholds, and demographic identifiers—occupy units and face displacement when rising rents exceed their budget or eviction risk thresholds. Vacant units may then be filled by higher-income in-migrants. NbS scenarios are introduced exogenously, locally boosting livability scores and triggering rent uplifts that propagate through the spatial grid. Over multi-year simulations, the model tracks rent burdens, forced displacement events, and shifts in population makeup, enabling side-by-side comparison of greening impacts in both wards under a baseline 'no-policy' scenario and alternative housing-policy regimes.

Results show that, without housing safeguards, NbS raise rents significantly—by roughly 20–25% over ten years—displacing thousands of low-income households. In Ward 57, this reinforces existing privilege as affluent renters easily absorb price increases, whereas in Ward 79 it displaces predominantly Black African households and Coloured households, substituting them with higher-income newcomers. Introducing inclusionary housing requirements—which reserve a substantial share of units near NbS sites for affordable rents, dampens rent inflation, retains most incumbent households, and preserves socio-economic diversity. Time-limited rent subsidies yield similar short-term relief but fail to prevent eventual displacement once support expires.

These findings underscore that NbS, while delivering environmental and recreational benefits, can exacerbate urban inequality unless paired with deliberate affordability measures. To achieve just transitions, Cape Town's green-infrastructure initiatives should be coupled with inclusionary zoning, dedicated affordability funds, and robust community engagement processes that empower residents and monitor displacement risks. By integrating climate-adaptation investments with housing-equity policies, cities can ensure that ecological solutions do not become drivers of social exclusion.

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With all that said, a final shoutout to Anjappar for providing me with crispy Mysore Masala Dosas in the middle of Den Haag, and to Rhys for eating them with me!

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Positionality Statement

My training as a mechanical engineer and social anthropologist has consistently placed me at the boundary where technology and society interact, this was further reinforced through my masters in engineering and policy analysis. This thesis is a product of that positionality, and it is an endeavour in exploring that intersection further, by situating engineering tools within a larger social context.

Through this thesis, I have attempted to delve into some of the development challenges in Cape Town. However, I have unfortunately not had the means to visit, which is a big limitation to my understanding of the city, its problems, and therefore this work. My perspective has been shaped by open source scholarly literature and secondary data rather than personal observation, a limitation I acknowledge in the thesis's limitations section. I have also attempted to integrate African scholarship alongside Western theory to root the thesis in a localised context.

Further, this research uses agent-based modeling as a proof of concept, a tool that was largely built on western standards. I have tried to maintain the awareness that it cannot yield directly transferable results for a Global South context and risks reinforcing techno-solutionism; I therefore invite readers to approach its insights with caution. Guided by Maurice Merleau-Ponty's assertion that "the body is our general medium for having a world" (Merleau-Ponty, 2012, p. 147), I recognize that simulations highlight spatial patterns—how residents might move, cluster around green spaces, or respond to policy scenarios—but inherently simplify the emotions, memories, and social dynamics that give urban life its texture.

In interpreting model outputs, I have attempted to establish the existence of segregation and the creation of exclusive access as a result of urban greening. Instead of focusing on the exact numbers produced by the model, I have tried to focus on capturing the phenomena that take place when greening initiatives are implemented, and their causal relations. I echo Couldry and Mejias's warning of "data colonialism" (Couldry & Mejias, 2019) and Morozov's critique of techno-solutionism (Morozov, 2013), as I urge the reader to interpret this text as a proof of concept and not a decision support tool with deterministic outputs. Throughout, I have attempted to remain humble about the limits of my vantage point, stay open to feedback from those with lived experience in Cape Town, and aimed to produce research that is both methodologically robust and attentive to the city's own aspirations for equitable and sustainable urban futures. However, it must be stated that I am a masters student with a limitation of time and skills, and the thesis has therefore, also been shaped greatly by my technical aptitude and defined timeline.

And now I must say something that feels necessary—not just as context, but as content. Writing this thesis took place alongside horrific, global events that have made it impossible to treat academic work as separate from the world, and the self. The genocide in Gaza, the war between India and Pakistan, the attacks on Iran, and the daily images of violence, death, and displacement—especially of children—formed the backdrop of these past months. It is not normal to open the news to images of bombed schools and grieving families in the morning, and then calmly proceed to write code in the afternoon. And it should not be normalized.

This thesis is a product of that dissonance. It exists because I believe engineering and modeling should serve people—not profit. It should be in the service of equity, of justice, and of the upliftment of those who have been pushed to the margins, not their further displacement or destruction. I cannot pretend that the current political events haven't shaped how I think, what I care about, or how I see my place in the world. They have, entirely.

In closing, I urge all academics and everyone in the business of knowledge production to never lose sight of the power they hold. Knowledge, when detached from the world it claims to describe, risks becoming irrelevant—or worse, complicit. Research should not sit on shelves or behind paywalls, but move, intentionally and urgently, toward making people's lives better.

Chapter 1: Introduction

Cities around the world are increasingly turning to Nature-Based Solutions (NbS) in urban planning as integrative strategies to tackle climate change and other environmental challenges while also improving livability. NbS are broadly defined as ecosystem-driven interventions designed to address societal challenges (such as flooding, heat stress, or air pollution) in ways that enhance human well-being and environmental resilience (Dunlop et al., 2024). In practice, NbS can encompass green infrastructure like urban forests, parks, green roofs, bioswales, and wetland restorations – all aimed at making cities more sustainable and resilient (Albert et al., 2019). These interventions promise multiple co-benefits: for example, expanding urban green spaces can reduce flood risks and mitigate urban heat islands (Biasin et al., 2023), and adding green amenities such as parks or bioswales can even increase surrounding property values by improving neighbourhood attractiveness (Mutlu et al., 2023). Cape Town, like many global cities, has begun implementing NbS to enhance climate adaptation and redress environmental deficits in underserved areas. However, an emerging concern is that the very environmental improvements brought by NbS may carry unintended social costs. Scholars note a tension between the *ecological benefits* of NbS and potential *distributional injustices* they might trigger in urban communities (Cousins, 2021; Osaka et al., 2021). In particular, new green amenities can spur rising property values and living costs, potentially displacing lower-income residents – a phenomenon often termed "green gentrification." This thesis investigates that tension in the context of Cape Town's historically marginalised areas, asking how NbS initiatives might lead to urban displacement or exacerbated inequalities in a post-apartheid city landscape. The study focuses on two wards (City of Cape Town's Wards 57 and 79) and employs an agent-based modeling approach to simulate different NbS implementation scenarios. By examining who benefits and who bears the burdens when green infrastructure is introduced, the research sheds light on the distributional effects of NbS in Cape Town's unique socio-spatial context.

1.1 Academic and Societal Relevance

This research sits at the intersection of urban environmental planning, social justice, and computational modeling, addressing a gap in both academic literature and practical policy. Academically, it contributes to a growing body of work on justice and equity in nature-based solutions. While NbS have been widely studied for their technical performance and ecological outcomes, fewer studies explicitly interrogate their social implications in the Global South. Recent research calls for putting questions of race, class, and inequality at the core of NbS assessments (Cousins, 2021; Van der Laarse, 2023), reflecting an evolving recognition that sustainability interventions must be evaluated not just on ecological metrics but also on their social distribution of costs and benefits. By focusing on Cape Town this thesis provides an important case for examining "green justice" in urban adaptation strategies. It extends prior work on green gentrification (e.g., Anguelovski et al., 2018) into a developing world context, thereby broadening the geographic scope of gentrification research which has largely centered on North American and European cities. The use of agent-based modeling (ABM) in this study also contributes methodologically; ABM is still a relatively novel tool in urban planning research for simulating bottom-up processes like household relocation and housing market dynamics (Mutlu, Roy, & Filatova, 2023). Demonstrating ABM's utility in exploring NbS scenarios offers a methodological contribution to urban studies and complexity science. This has been further discussed in the research gaps section.

Additionally, Cape Town's municipal authorities and South African policymakers face the dual challenge of redressing apartheid-era inequalities while also building resilience to climate change. NbS such as restoring wetlands to manage floods or planting trees to cool heat-stressed neighbourhoods are increasingly on the policy agenda (City of Cape Town, 2021). However, if these green investments end up pricing out the very communities they intend to help, the social backlash could undermine public support for sustainability initiatives and worsen urban segregation. The findings of this thesis will be relevant to urban planners, environmental officials, and housing policymakers in Cape Town and other cities with similar histories. By highlighting potential unintended consequences (like displacement or "eco-apartheid") and exploring conditions under which NbS can be implemented more equitably, the research can inform policy design – for instance, emphasizing the need for affordable housing measures or community land trusts alongside greening projects. More broadly, this study speaks to global conversations on just urban transitions: it exemplifies how cities might pursue climate resilience and environmental quality improvements without reproducing social injustices. The work thus aligns with international calls (e.g., by the United Nations and urban coalitions) to ensure that climate adaptation and sustainability efforts also advance equity and inclusivity. In sum, the thesis is an attempt at being both timely and important: it addresses a pressing urban sustainability question (how to achieve greener cities without displacing vulnerable residents) that carries real-world stakes for communities and decision-makers.

1.2 Identifying the Problem

1.2.1 Societal Challenge and Context

The core problem addressed in this thesis emerges from a grand societal challenge: how can cities implement environmental innovations to combat climate change and improve livability, *without* exacerbating social inequality? NbS are often promoted as "win-win" interventions that simultaneously deliver ecological and social benefits, yet on closer examination the balance of those benefits can be uneven (Kandel & Frantzeskaki, 2023). Achieving urban resilience is not just a technical endeavor but also a social one – it requires asking *"Resilient for whom?"* (Frantzeskaki & McPhearson, 2022). In many cities, new parks, greenways, or greened waterfronts have led to rising rents and the influx of wealthier residents, pushing out long-time lower-income communities. This dynamic of environmental improvement followed by displacement has been documented in various contexts and is encapsulated in the notion of green gentrification (Anguelovski et al., 2018). On one hand, NbS offer clear benefits: cleaner air, cooler microclimates, reduced flood risk, aesthetic and recreational value, and even economic uplift in the form of new local jobs or increased property investments. On the other hand, these improvements can translate into higher property prices and living costs, benefiting homeowners and developers while straining or displacing renters and poorer households. *Who* gets to enjoy the improved urban environment and *who* might be forced to leave are questions of distributional justice central to this problem. The literature has begun to emphasize that NbS are not a panacea or "silver bullet" and must be planned with careful attention to social outcomes and trade-offs (Frantzeskaki & McPhearson, 2022; Osaka et al., 2021). If implemented without an equity lens, even the most well-intentioned "green" projects can inadvertently reinforce existing inequalities or create new forms of exclusion. This thesis zeroes in on that dilemma, examining the distributional impacts of NbS and highlighting the potential tension between ecological gains and social equity in an urban context.

1.2.2 South Africa's Spatial Landscape: Background and History

Cape Town in particular is frequently cited as one of the world's most segregated and spatially unequal cities (Turok et al., 2021). Decades of institutionalized racial segregation (from the 1950s to early 1990s) engineered an urban form where predominantly White, higher-income communities occupied well-located, amenity-rich areas (often close to the coast or city center), while Black African households and Coloured communities were forcibly relocated to the periphery – the area known as the Cape Flats. This legacy has profound implications for the distribution of urban green space and environmental quality. A recent nationwide assessment found that *"virtually all (96%) of South African cities remain under a form of green apartheid,"* (South African Local Government Association, 2020) meaning greener, leafier environments overwhelmingly coincide with wealthier (largely White) neighbourhoods, whereas low-income townships have significantly less vegetation and park access (Venter et al., 2020). In Cape Town, the historically marginalised districts – such as many parts of the Cape Flats – have far fewer public parks, street trees, and green corridors than the city's wealthy enclaves. These same disadvantaged areas also face higher exposure to environmental hazards: they tend to be more flood-prone (due to inadequate stormwater infrastructure in flat, low-lying terrains) and suffer more intensely from extreme heat (due to sparse tree cover and the urban heat island effect) (Van der Laarse, 2023). The term "green apartheid" has been used by local observers to describe this pattern, wherein environmental amenities are segregated along racial and class lines just as housing once was (Woroniecki et al., 2020).

Cape Town's authorities have recognized these disparities and, in policy rhetoric, committed to reversing them – for instance, through climate adaptation plans that call for equitable distribution of green infrastructure (City of Cape Town, 2021). Nature-based Solutions are envisioned as part of this healing process: restoring degraded wetlands in flood-prone townships, planting trees and establishing parks in under-served neighbourhoods, and so forth. *However*, without accompanying social safeguards, such well-meaning interventions could trigger eco-gentrification. In a city still deeply scarred by apartheid geographies, an influx of investment in the Cape Flats (for example, creating new green belts or recreational parks) may attract higher-income interest in those areas, unless protective measures are in place. The societal challenge identified here is thus twofold: Cape Town *must* improve environmental conditions in its poorer districts to achieve climate resilience and redress injustices, *and* it must do so in a way that does not inadvertently replicate the exclusionary patterns of the past.

1.3 NbS Implementation

The City Council of Cape Town's official policies emphasize their desire to expand urban greening and promote equity. The Climate Change Action Plan and Biodiversity Management Report call for expanding vegetated infrastructure (e.g. parks, green belts, green roofs) to mitigate heat islands, manage stormwater, and enhance biodiversity (City Council of Cape Town, 2020a; City of Cape Town, 2023). Green roofs and community gardens directly support these goals by converting impervious surfaces into cooling, vegetated areas with habitat value. They also support long-term climate resilience and local economies (e.g. jobs in garden maintenance). By aligning with the City's mandated greening and climate resilience targets, green roofs and gardens advance the City's sustainability agenda. For example:

- Climate mitigation and adaptation: Green roofs are explicitly mentioned in Cape Town's urban greening programmes to reduce heat and manage water (Climate Action Plan, 2020a).

Community gardens similarly support local food security and drought resilience (per the City's Biodiversity and Urban Agriculture policies).

- Biodiversity and open space: Both interventions create new habitat patches in dense areas, supporting the City's goal of enhancing urban biodiversity corridors (Biodiversity Progress Report 2023). Community gardens often incorporate indigenous plantings and water-wise practices aligned with the City's guidelines.
- Transparency and participation: The City's Open Data and participatory governance policies (Open Data Policy, 2020b) encourage community involvement and data-driven planning. Community gardens inherently engage residents in site design and upkeep, and green-roof projects on public buildings can involve local schools or NGOs, fitting the City's emphasis on collaborative stewardship.

Green roofs and gardens advance Cape Town's resilience and equity objectives by delivering distributed benefits across social and environmental dimensions. On the resilience front, these NbS cool urban temperatures, absorb stormwater, and increase local food and water security — all key to coping with Cape Town's heatwaves, floods, and droughts. They also enhance social resilience by creating gathering spaces and improving wellbeing. Crucially, these interventions embody the City's equity and participation goals. The Climate Action Plan stresses that collaborative, city-wide action is needed to ensure benefits reach vulnerable groups (Climate Action Plan, 2020a). By design, community gardens empower disadvantaged neighbourhoods with ownership and skills-building, while green roofs on community centers or libraries can be managed by local groups. Incorporating gardens and roofs can engage residents in planning and ensure that climate solutions serve all. Therefore, community gardens and green roofs are the most suitable NbS to the selected wards.

- Equitable benefits: Both NbS provide environmental services that disproportionately help lower-income areas (e.g. reducing extreme heat in dense neighbourhoods, improving air quality). This aligns with the City's commitment to "leave no one behind" in climate adaptation (IDP/LED Strategy). In practice, community gardens particularly support food security, health, and livelihoods in underserved communities.
- Community participation: The City's strategic plans call for active citizen involvement in green initiatives. By their nature, community gardens require local stewardship and create "third places" for social capital, while green roofs can include public access or school education programs. These features respond to the City's goal of social inclusion in sustainability projects.

1.4 Purpose of the Study

The purpose of this research is to critically explore and illuminate the distributional effects of implementing NbS in Cape Town, with the ultimate goal of informing more equitable urban environmental planning. In service of this goal, the study is guided by a central research question: *What are the distributional effects of implementing Nature-Based Solutions in Cape Town?* In other words, when green infrastructure projects are introduced in a spatially unequal, post-apartheid city, how are the benefits (like improved livability and resilience) and burdens (like rising costs or displacement pressures) allocated among different groups and areas? The thesis will answer this question from the perspective of rent increases and the subsequent displacement of renters. By answering this question, the thesis aims to uncover whether NbS, as applied in Cape Town's Cape Flats, risk reinforcing existing socio-spatial inequalities or can be designed to help alleviate them. The relevance of the results lies in both theoretical and practical realms. Theoretically, the findings will deepen our understanding of green gentrification dynamics, particularly in a Global South context that has been underrepresented in empirical studies of gentrification and urban greening. The Cape Town case can offer insights into how historical segregation and land ownership patterns mediate the impacts of new environmental interventions – insights that may differ from patterns observed in Western cities and thus enrich global urban theory. Practically, this research provides evidence-based foresight for planners and communities: it identifies potential unintended consequences of NbS rollouts (such as short-term spikes in housing prices or longer-term demographic shifts) and evaluates scenarios under which those consequences might be mitigated. However, it must be noted that the empirical results are one proxy of distributional effects of a green intervention, very specifically measured as rent increases. The larger aim is not to determine the exact number of people who will be displaced, rather, it is to establish that displacement will take place and will affect people of different racial identifications, differently. This aim is derived from the understanding that the contribution of the social scientist is not always to discover new phenomena, but to re-establish the existence of social institutions over time, and track the manifestations of their development.

In pursuit of this purpose, the thesis employs an Agent-Based Modeling (ABM) methodology. ABM is introduced as a powerful tool in this context because it can simulate the complex interactions of individual agents (residents, landlords, developers, etc.) in the housing market in response to changes in the environment. By constructing a computational model of the two case study areas (Wards 57 and 79 in Cape Town) and "rolling out" virtual NbS (e.g. adding parks or green infrastructure) in the simulation, the research can observe emergent outcomes such as changes in rents, displacement of households, and shifts in neighbourhood composition over time. This scenario-based approach provides a preview of possible futures. By briefly previewing the methodology here, it is worth noting that ABM offers advantages in capturing the bottom-up nature of gentrification processes (e.g., numerous individual decisions to move or invest) that aggregate into macro-level patterns. This approach aligns with the thesis's aim to not only identify potential problems but also explore solutions: through simulation, the research tests *"what if"* questions (e.g., *What if a new park is added in Ward 79? What if that is combined with a rent subsidy or an inclusionary zoning policy?*) in order to derive policy-relevant insights.

In conclusion, this introduction has established the context and importance of studying NbS-driven green gentrification in Cape Town. It has defined NbS and situated them within a broader debate about environmental justice in cities, highlighted the unique spatial inequalities of Cape Town's post-apartheid landscape, and articulated the research question and objectives guiding this thesis. The chapters that follow will build on this foundation: first by reviewing relevant literature on NbS, urban inequality, and agent-based modeling, then by detailing the research design and model implementation, and finally by presenting simulation results and discussing their implications. Ultimately, the aim is to ensure that as cities like Cape Town invest in nature-based solutions for a sustainable future, they do so in a manner that is socially just and inclusive – avoiding the trap of "solving" environmental problems at the expense of exacerbating social ones.

Chapter 2: Literature Review

The project began with an extensive literature review. Several search bases like *Scopus* and *Google Scholar* were used, along with a vast amount of snowball sampling from initially identified relevant papers. Tools like *Connected Papers* were used for exploring literature that was adjacent to the identified core papers. This mixed approach to the literature review led to a holistic understanding of how nature based solutions are deployed as pilot projects in cities with Developing County status. It also contributed to a comprehensive overview of the current standard for using agent based modelling for studying displacement and gentrification phenomena. All of this knowledge cumulatively contributed to designing the methodology which integrates historical contexts with spatially explicit agent based modelling.

2.1 Nature Based Solutions

Nature-based solutions (NbS) are defined broadly as ecosystem-focused strategies designed to address societal challenges while simultaneously enhancing human well-being and ecosystem resilience (Dunlop et al., 2024; IUCN, 2016). They encompass green infrastructure such as urban forests, parks, green roofs, bioswales, and wetland restoration, addressing issues like flooding, heat stress, pollution, and biodiversity loss (Albert et al., 2019). Despite their ecological advantages, the literature increasingly emphasizes the necessity of evaluating NbS from social and economic perspectives, given that their implementation often involves trade-offs affecting different urban populations unequally (Cousins, 2021; Osaka et al., 2021).

For example, Biasin et al. (2023) demonstrate that implementing NbS interventions such as expanding urban green areas can effectively reduce urban flooding and mitigate heat island effects, providing measurable protective benefits for city residents. Likewise, Mutlu et al. (2023) found that introducing NbS for flood protection in the Netherlands not only improved safety but also increased nearby property values; homeowners were willing to pay roughly a 15% premium for houses close to the new green flood-control amenities. Such outcomes hint at the potential for NbS to simultaneously enhance urban quality of life and economic value. In summary, NbS in cities are conceptualized as integrative solutions that generate environmental resilience, social well-being, and economic gains in tandem. Yet, as the following sections elaborate, realising these multiple benefits in practice requires careful evaluation of trade-offs and explicit attention to who actually benefits from NbS initiatives.

2.1.1 Assessing Trade-offs of NbS

Despite the appealing narrative often surrounding NbS, scholars emphasize the importance of scrutinizing the trade-offs and less tangible impacts that NbS projects can entail. By design, NbS seek to balance ecological, social, and economic goals, but achieving all objectives equally is challenging. Implementing a new urban park or wetland, for example, might require repurposing land or public funds that were serving other needs, leading to trade-offs between different community values or budget priorities. Many social and cultural outcomes of NbS are also difficult to quantify, such as: changes in community identity, sense of place, or informal land-use practices. These aspects are thus often overlooked in standard project evaluations (Biasin, Masiero, Amato, & Pettenella, 2023). Moreover, benefits and costs of NbS can be uneven in time and space: some positive outcomes (like biodiversity gains or aesthetic improvements) may only manifest in the long term, while certain costs or disruptions (like the loss of informal livelihoods or displacement of cultural practices tied to land) occur immediately.

Osaka et al. (2021) note that simply labeling an intervention as “nature-based” or “natural” often carries an implicit assumption of inherent goodness. NbS are frequently framed as more beneficial, cost-effective, and democratic compared to traditional grey infrastructure alternatives. This favorable framing can divert attention from actual performance and context-specific trade-offs. Under greater scrutiny, so-called natural solutions can turn out to be just as risky, expensive, or technocratic as engineered solutions if not planned carefully. Another concern is that participatory planning, often touted as a strength of NbS governance, does not automatically guarantee equitable or inclusive outcomes. Woroniecki et al. (2020) caution that while involving multiple stakeholders is essential, underlying power imbalances can subvert the process. In some cases, participatory processes for NbS become tokenistic; local knowledge or marginalised groups’ priorities may be overridden by technical experts or external funders’ agendas (Berry, 2023). This phenomenon has been described as a form of *epistemic violence* in urban development, where certain ways of knowing or valuing nature are excluded or devalued.

If NbS projects impose external notions of nature and fail to respect community knowledge, they risk reinforcing the very inequities they seek to solve. In short, a critical evaluation of NbS implementation requires acknowledging trade-offs (e.g. ecological gains *versus* socio-economic losses) and making deliberate efforts to assess the harder-to-measure social impacts.

2.1.2 Green Gentrification

Importantly, new NbS interventions can also produce unintended distributional drawbacks. A growing literature on green gentrification documents how introducing attractive green spaces into under-invested urban areas can drive up property values and living costs, ultimately displacing some of the very communities that NbS were meant to benefit (Anguelovski et al., 2018). A recent quantitative study across 28 cities in North America and Europe provides strong evidence of this trend. Using spatial data from the 1990s–2010s, Garcia-Lamarca et al. (2022) found a “strong positive and relevant relationship” between intensive greening in the 1990s–2000s and subsequent gentrification between 2000–2016 in 17 of the 28 cities examined. In these cities, neighbourhoods that saw significant new green infrastructure were far more likely to gentrify in the following decade, pricing out lower-income residents and renters. In other words, the creation of new parks and greenways often correlates with an influx of higher-income residents and rising rents/property prices, unless preventative measures are in place. The benefits of NbS can thus accrue disproportionately to newer, wealthier residents and real-estate developers, while long-time residents face displacement pressures or exclusion. Such outcomes represent a failure of distributional justice, rebranding NbS from a remedy for urban ills into a contributor to inequality (Van der Laarse, 2023).

Understanding and anticipating the complex socio-economic impacts of NbS, including the distributional effects discussed above, is a challenging task. Urban systems involve many interacting agents (residents, developers, businesses, government entities), and NbS interventions can trigger non-linear ripple effects across neighbourhoods and social groups. To analyze these dynamics, researchers are increasingly turning to quantitative modeling tools, with a particular enthusiasm for agent-based modeling (ABM). This is particularly difficult for Global South Contexts where data and resources are scarce, and multiple assumptions need to be made in order to model social phenomena. For South Africa and especially Cape Town, studying gentrification will always be a twofold problem. Firstly, because of the inherent correlation between income and race, certain sections of society will always be disadvantaged. Secondly, the implemented developmental project will affect everyone differently due to the multiple intersectional inequalities the.

2.1.3 Agent Based Modelling: Establishing Relevance

Agent-Based Modeling is a computational simulation approach that creates artificial societies of individual *agents* (e.g. households, firms, or even government decision-makers), each following certain behavior rules, and then explores how their interactions lead to emergent outcomes at the community or city scale. This approach is well-suited to NbS impact analysis because many distributional outcomes arise from the bottom-up decisions of individuals and their interactions in markets or communities (Gilbert, Hawksworth, & Swinney, 2009). For example, whether an urban greening project leads to gentrification depends on myriad individual decisions: homebuyers deciding where to move, landlords setting rents, residents deciding whether to stay or relocate, entrepreneurs opening businesses to serve new park visitors, etc. ABM allows researchers to explicitly simulate these processes and test different scenarios.

A notable application of ABM in the NbS context is studying how new green spaces might influence local economies and land-use patterns. Koppelaar et al. (2021), for instance, developed an agent-based model to examine the impact of adding urban parks on neighbourhood retail in four European cities. In their simulation, resident agents would walk to parks and nearby shops, and shop-owner agents would decide whether to open businesses based on foot traffic. The model demonstrated that the presence of a large green park can indeed boost visits to local cafes and kiosks around its edges, leading to the emergence of new retail shops to meet the increased demand. In the case of one mid-sized city (Szeged, Hungary), a park attracting ~800 walking visitors could support 5–6 new small shops, while in a larger city (Milan, Italy), a park drawing ~2,900 visitors might sustain a dozen or more shops in the vicinity. This provides quantitative evidence of an indirect economic co-benefit of NbS: greener neighbourhoods can stimulate local commerce and job creation via increased recreation and foot traffic. Such insights are difficult to obtain without a simulation that links human behavior (where people choose to walk and spend money) with environmental changes (the introduction of parks). The ABM also allowed Koppelaar et al. (2021) to experiment with different spatial configurations of green space, for example, comparing one large centralized park versus several smaller pocket parks to see how the spatial distribution of NbS affects economic outcomes. They found that a single large park tends to concentrate activity and create a commercial hub at its perimeter, whereas multiple smaller green spaces distribute activity more diffusely, which can lead to different patterns of retail development (e.g. more numerous but smaller shops spread out in a neighbourhood). Insights like these can inform urban planners about how to design NbS for desired economic outcomes.

Beyond local economic changes, ABM has been applied to explore the housing market and demographic impacts of urban greening (Parker et al., 2002). By coupling agent decision-making with housing price dynamics (through, say, a hedonic pricing component), one can simulate how different households might relocate in response to NbS-driven changes in neighbourhood attractiveness. The strength of ABM in this domain lies in its ability to represent heterogeneity (different types of agents with varied incomes, preferences, and constraints) and emergent complexity. Cities consist of diverse actors, from informal settlement dwellers to wealthy developers, whose responses to an NbS will vary widely. ABM can incorporate this diversity (e.g. rules like "a family will move if rent exceeds X% of income" or "a developer will build luxury housing if park-view prices rise above threshold Y") and then reveal the collective outcomes that emerge from these micro-decisions. Especially for a city like Cape

Town, with highly heterogeneous communities and a history of segregated development, ABM offers a way to simulate how an intervention in, say, the Cape Flats might play out. As Koppelaar et al. (2021) argue, simulation provides a useful ex ante assessment tool for NbS, helping ensure that the benefits can be sustained and shared fairly in the long run.

2.2 Research Gap

While the potential benefits of NbS are well documented, there remains a clear gap in understanding their social and distributional implications, especially in fast-growing cities of the Global South. As noted above, issues like displacement (green gentrification), unequal access to NbS amenities, and community empowerment have only recently begun to garner research attention, often as qualitative case studies or critical essays rather than systematic, quantitative analyses. Woroniecki et al. (2020) and Cousins (2021) both highlight that without an intentional focus on justice, NbS projects risk reproducing the very inequalities they aim to alleviate. This warning is particularly salient in the context of cities like Cape Town, which are characterised by deep historical inequities and segregation.

One major hurdle is the lack of empirical data on long-term socio-economic outcomes of urban NbS in the Global South. Green gentrification, for instance, has been well documented in North America and Europe (Anguelovski et al., 2022), but there is little quantitative evidence of if and how similar processes might unfold in African or South Asian cities. In contrast to Global North contexts—where high-resolution spatial, demographic, and longitudinal housing data are often readily available—this study contends with significant data gaps that constrain traditional forms of quantitative analysis. To address this, the research employs a spatially explicit agent-based model as a proof of concept, simulating displacement and demographic change under different NbS scenarios in Cape Town. The model is necessarily built on several assumptions—such as full rental occupancy, uniform initial household distribution, and income-based thresholds for displacement—that would likely be refined or empirically validated in Global North studies with richer datasets. These simplifying assumptions are not flaws but deliberate methodological adaptations that allow the research to investigate systemic distributional patterns in data-constrained environments. In doing so, the study demonstrates how simulation-based approaches can help surface plausible equity risks and inform forward-looking policy design in under-researched urban contexts.

Despite the growing enthusiasm around NbS as multi-benefit solutions for urban sustainability, there remains a critical gap in understanding how their benefits and burdens are distributed across different social groups. Existing literature increasingly acknowledges that NbS do not automatically deliver equitable outcomes, and without deliberate governance mechanisms, they may exacerbate existing urban inequalities. However, most studies stop at recognizing this problem in principle; few provide systematic, spatially grounded analyses of how these distributional dynamics actually unfold in practice. The lack of empirically grounded, context-sensitive research on the socio-economic effects of NbS—particularly in historically segregated and data-constrained cities—underscores the need for targeted investigation. This thesis responds to that need by directly interrogating the equity implications of NbS implementation in Cape Town, a city where such trade-offs are not theoretical but material and urgent.

Against this backdrop, the present study's focus on the distributional effects of NbS in Cape Town directly engages with these knowledge gaps. The foregoing review highlighted that while the ecological effectiveness of NbS (their capacity to deliver ecosystem services) is increasingly well documented, their social ramifications remain under-researched and poorly understood. By concentrating on these questions, this thesis aims to advance the discourse from broad calls for equity to a concrete analysis of equity outcomes in a specific locale. The use of agent-based modeling and scenario planning for the Cape Flats context is intended as a proof of concept approach that builds on prior work (such as Koppelaar et al.'s economic simulations and Mutlu et al.'s pricing analysis) and adapts it to address socio-economic complexities. This approach allows for a systematic exploration of hypothetical futures, effectively turning the lack of empirical data into a research opportunity: in the absence of extensive real-world evidence on NbS-driven gentrification or social change in Cape Town, the study will generate data based insight by simulating these processes. In doing so, it provides an evidence-based examination of concerns that community activists and planners have raised, for example, could green revitalization lead to a form of *"eco-apartheid"* if not coupled with social safeguards, and conversely, how can NbS be designed to maximize benefits for historically disadvantaged communities?

2.2.1 Research Questions

Consequently, this research aims to systematically explore the central research question:

What are the distributional effects of implementing nature-based solutions in Cape Town?

This primary question is structured further through the following sub-questions:

1. What potential NbS implementation scenarios can be developed to study distributional effects?
2. How can the conceptualized NbS scenarios be operationalized in an agent based model?
3. What are the distributional effects of the implemented NbS on different communities within Cape Town?

Ultimately, this literature review underscores that achieving truly sustainable and resilient cities with NbS is as much a social challenge as an ecological one. The synthesis of existing research reveals a gap between the aspirational rhetoric of NbS, the idea that nature can heal cities in one broad stroke, and the reality of implementation on unequal urban terrains. By seeking to bridge this gap through focused analysis of distributional outcomes, the current research is justified and timely. Its findings will aim to inform practical strategies for city authorities and stakeholders in Cape Town (and similar cities) on how to implement NbS in ways that are environmentally sound and socially equitable.

Chapter 3: Method

3.1 Case Study: Cape Town

3.1.1 Selection of Wards

The model is applied to two specific wards in Cape Town, selected to represent contrasting socio-economic and urban contexts. Ward 57 (the neighbourhood of largely Observatory and Salt Lake) is a relatively affluent area, whereas Ward 79 (the neighbourhood of Mitchell's Plain) is a lower-income, high-density ward. This deliberate choice allows the study to compare how NbS might trigger different responses in different urban settings.

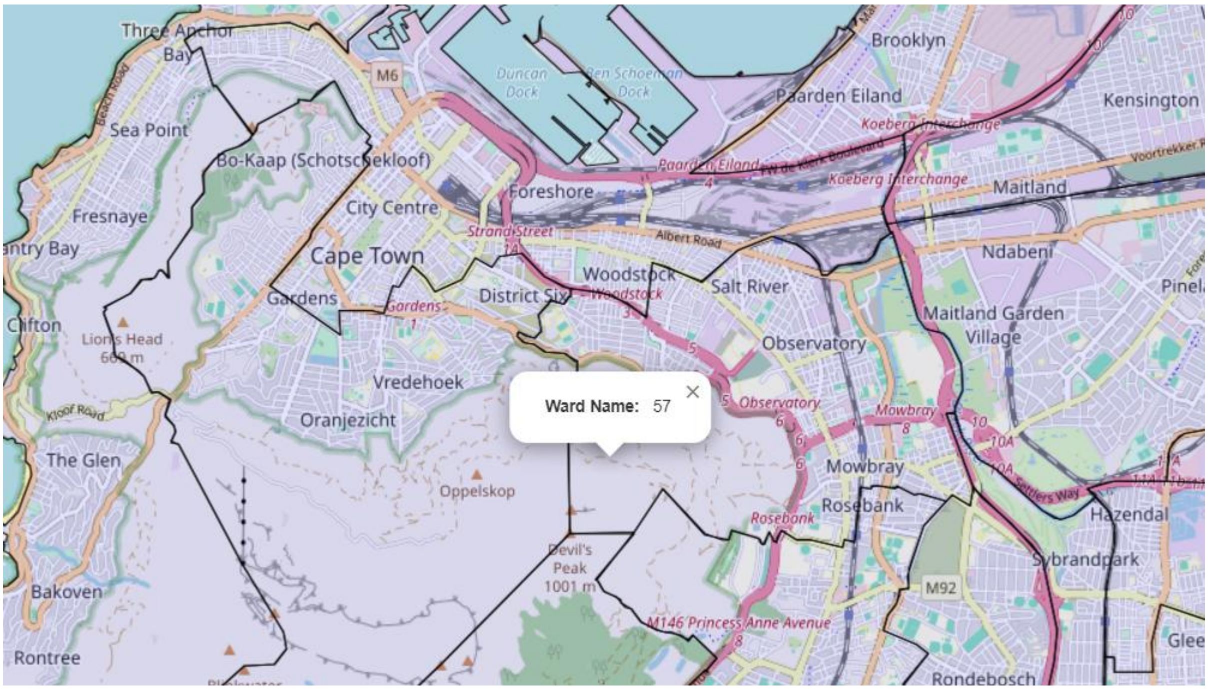


Figure 1: Ward 57 in Open Street Maps overlaid with 2011 South African Census Ward Boundaries

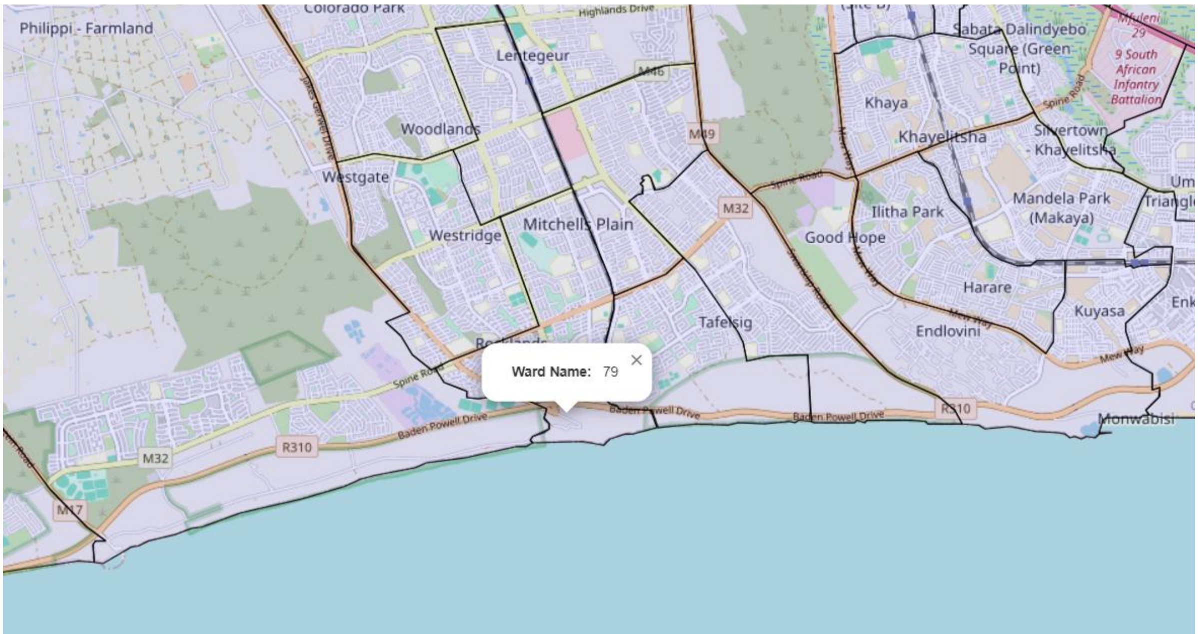


Figure 2: Ward 79 in Open Street Maps overlaid with 2011 South African Census Ward Boundaries

By examining an affluent ward versus a vulnerable community, the model can capture heterogeneous gentrification dynamics and equity outcomes. Such a comparative approach is important because the effects of urban greening are known to vary with the baseline characteristics of neighbourhoods (Gori Nocentini, 2019). In wealthier areas, added green amenities may enhance property values and quality of life without displacing the incumbent residents (who can typically absorb or even welcome the value uplift). In contrast, greening in historically disadvantaged or low-income areas can inadvertently lead to green gentrification, where environmental improvements attract higher-income interest and drive up housing costs, displacing long-term residents (Gori Nocentini, 2019). The literature documents many cases where greening projects in lower-income neighbourhoods resulted in the exclusion of the very residents they were meant to benefit, as rising rents and property values forced them out.

By calibrating the model separately for each ward, an attempt has been made to capture local demographic, economic, and housing characteristics that influence agent behavior. This ward-specific approach recognizes that neighbourhood context matters: urban social-ecological processes are not uniform citywide, but are mediated by local conditions such as income levels, housing stock, population density, and existing green space access (Wijsman & Berbés-Blázquez, 2022). Comparing Ward 57 and 79 helps ensure the model captures a range of possible outcomes of NBS interventions, from minimal displacement to pronounced gentrification, thereby informing more equitable urban green development strategies.

Ward 57 and Ward 79 exemplify Cape Town's socio-spatial contrasts, so they gain from NbS in different ways. Ward 57 is a mixed-use, relatively affluent area with many existing gardens but still faces urban heat stress and flooding on paved streets. Here, green roofs on apartments or businesses would further expand green cover and provide climate buffering without requiring scarce ground space. In contrast, Ward 79 has very limited green space and high vulnerability: dense housing, fewer parks, and greater heat/flood risks. Numerous studies note that historically disadvantaged areas like Mitchell's Plain have far poorer access to parks and urban nature. Thus, installing community gardens here directly addresses this gap: providing fresh produce, jobs, and youth education, as well as safer outdoor spaces. Green roofs on local schools or clinics would cool buildings and reduce runoff in a water-stressed township. Socially, gardens in Mitchell's Plain can strengthen community networks and local food sovereignty much more than similar projects in Observatory. In short, while both neighbourhoods benefit environmentally (cooling, biodiversity) and socially (recreation, well-being), the socioeconomic payoff differs: observatory's implementations may focus on technology demonstration and amenity enhancement, whereas Mitchell's Plain projects yield critical services like food, income, and health improvements.

- *Ward 57 (affluent, mixed-use):* Likely high participation capacity and green awareness. NbS here can serve as demonstration sites, improve local microclimate, and add aesthetic value. There is a risk that greening in Observatory could indirectly raise property values, so careful design is needed to ensure inclusivity.
- *Ward 79 (historically disadvantaged):* Faces higher heat stress and food insecurity. NbS here fulfill urgent needs: lowering temperatures in informal areas, reducing flood damage, providing affordable nutrition, and creating jobs. Community-driven green projects also support social cohesion and healing in a community with limited public spaces.

Both cases illustrate the City's dual goals: resilience (reducing heat/flood impacts) and equitable development (targeted benefits for the needy).

The contrast between Observatory and Mitchell's Plain underscores why studying NbS impacts across contexts is essential. Cape Town's spatial legacy means an intervention can uplift one community while straining another. For example, rooftop gardens in Observatory might improve the neighbourhood's quality of life but also make units more expensive, displacing lower-income residents. In Mitchell's Plain, gardens could empower locals, but without safeguards, outsiders or elites might capture the benefits. Thus, the same NbS solution may have unequal outcomes: differences in land tenure, social capital, and baseline infrastructure mean Observatory and Mitchell's Plain could experience different benefit levels and risks. This justifies a research approach that explicitly compares outcomes across neighbourhoods. By modeling and measuring these distributional effects (e.g. changes in local rents, access to greenery, and participant demographics), planners can ensure the City's NbS strategy truly advances climate justice and does not inadvertently worsen inequality.

3.1.2 Racial Classification in South Africa's 2011 Census

The project traces the patterns of displacement through a demographic lens, to further understand the thesis it is necessary to first understand the constitution of the racial categories in the South African census of 2011. In the 2011 census the official categories were Black African, Coloured, Asian, White, and Other. In practice these correspond to the four historically used groups from apartheid, plus a catch-all 'Other.' Stats SA explicitly emphasizes that "population group reflects the respondent's chosen identification and does not reflect any 'official' definition." (Statistics South Africa, 2012). Enumerators were instructed to record whatever category the person gave. In short, these labels are used for statistical grouping but are understood in the South African context to correspond to those historical racial categories. (Today the term "Coloured" is widely used within the South African community, though it was a creation of apartheid classification.)

The term 'Black African' encompassess all persons of indigenous African descent (Bantu-speaking ethnicities, e.g. Zulu, Xhosa, Sotho, Tswana, etc.). This group formed roughly 79% of the 2011 population. Black Africans live across South Africa, both in rural and urban areas, but in Cape Town they are concentrated in townships on the urban periphery (e.g. Khayelitsha, Langa).

‘Coloured’ refers to a distinct mixed-race community, traditionally of Khoisan, African, Malay and European ancestry. It is a South African term (Afrikaans *Kleurling*) dating to apartheid, it includes people whose heritage is mixed and who do not identify as Black African or White. Coloured people predominantly speak Afrikaans and are heavily concentrated in the Western and Northern Cape provinces. In Cape Town metro, Coloured communities occupy many neighbourhoods on the Cape Flats (e.g. Mitchells Plain, Khayelitsha has a significant Coloured population alongside Xhosa speakers).

Persons of South Asian (mostly Indian) or East Asian descent are classified as ‘Asian’. In practice this refers mainly to the descendants of 19th-century indentured Indian labourers (and later South Asian immigrants), and a smaller number of other Asians (e.g. Chinese, who historically might have been coded “Other” in earlier censuses). In 2011 this group was about 2–3% of South Africa’s population, concentrated largely in KwaZulu-Natal (Durban) and to a lesser extent in Gauteng and Cape Town.

Persons of European descent (mostly Afrikaans- or English-speaking families of Dutch, British or other European origin) are classified as ‘White’. Whites made up about 7–10% of the population, living chiefly in urban centers and suburbs. During apartheid they had privileged neighbourhoods and still today tend to live in the wealthier parts of cities.

‘Other’ refers to a small residual group (fewer than 1%) – typically people who do not identify with the above or who are recent immigrants (for example, Chinese or Middle Eastern South Africans often fall here).

These categories have very concrete spatial correlations in Cape Town due to apartheid-era planning. Predominantly white and high-income areas tend to be clustered (for example, city center suburbs are largely White) while Coloured and Black African communities occupy other districts. For instance, a recent study mapping Cape Town shows that white neighbourhoods on average lie much closer to parks and green space (about 700 m) whereas Black African households households African areas lie farther away (about 2.6 km) (Schell, 2020). Similarly, Coloured townships like Mitchells Plain are mainly in the Western Cape suburbs, and Indian/Asian residents are mostly in Durban but some live in Cape Town’s “high-up” suburbs like Sydenham. Thus, South Africa’s four official population groups remain tightly linked to geography: what urban planners term “green apartheid” means many urban improvements (like parks) disproportionately benefit historically white or affluent areas (Schell, 2020). These patterns mean that, for example, gentrification or rising rents in a Cape Town neighbourhood can affect racial groups differently – a phenomenon this thesis will attempt to explore and understand.

3.2 Model Description

This spatially explicit Agent-Based Model (ABM) simulates housing market dynamics and resident displacement in two distinct wards in Cape Town (Wards 57 and 79), under various scenarios involving Nature-Based Solutions (NbS). The model specifically investigates the distributional effects of NbS, focusing on green gentrification—the socio-economic displacement of lower-income residents due to rising rents and property values following environmental improvements.

By simulating micro-level interactions between households and their local environments, this ABM highlights differences in the distribution of NbS benefits between a relatively affluent area (Ward 57) and a densely populated, lower-income area (Ward 79). The model identifies the specific conditions that lead to NbS-driven displacement, estimates the magnitude and racial disparities of these impacts, and assesses the potential effectiveness of policy interventions to mitigate displacement, aligning with the actionable objectives set by the City Council of Cape Town. The full implementation of the simulation model is available in a public GitHub repository at: https://github.com/Ya-she/CT_NbS_ABM

The following sections detail the model's architecture, assumptions, and behavioral dynamics to support clear understanding and reproducibility.

3.3 Model Architecture

3.3.1 Agents and Objects

This section describes the key actors (agents) and environmental components (objects) of the ABM, clarifying their roles, characteristics, and interactions within the model. Each agent type represents a distinct stakeholder group involved in the housing market dynamics, and the objects (NbS interventions) represent critical scenario-driven environmental modifications.

PatchAgent: Each patch in the model represents a spatial grid cell, and its size is determined by the spatial resolution used in the simulation. Contrary to having only a single housing unit, each patch contains multiple housing units based on the actual density data of the ward. These patches function as localized housing markets, holding key attributes such as current average rent, an environmental livability score, and occupancy statuses. The livability score is a composite metric, constructed within the model to represent the relative quality of life in a given location. It combines environmental burden (pollution and heat levels), green infrastructure presence (via Nature-based Solutions), and social stability (occupancy rate). While not calibrated to real-world indices, this score provides a synthetic but interpretable measure of neighbourhood desirability, designed to evolve dynamically in response to NbS implementation and residential turnover.

PatchAgents maintain several important characteristics:

- Rent levels (which evolve due to environmental changes and market dynamics)
- Environmental livability scores (affected by nearby NbS)
- Number of housing units (based on density data)
- Occupancy statuses (number of vacant versus occupied housing units)

HouseholdAgent: Household agents represent resident households currently occupying housing units within the patches. Each household is characterised by a set of socio-economic attributes, such as income level, income growth over time, racial group identification, and initial ward affiliation. All households are modeled explicitly as renters to reflect the study's conceptual focus on forced displacement and not voluntary homeowner movements. Each timestep, household agents evaluate whether their current housing is affordable based on their income relative to the local rent. When rent exceeds their affordability threshold or when determined by a probabilistic eviction risk function, these households become displaced. Displaced households do not relocate within the model area; they are considered permanently moved out of the community, reflecting the primary study goal: tracking forced displacement rather than internal community churn.

Key properties collected by household agents include:

- Household income and income growth
- Socio-demographic identifiers (e.g., racial group, initial ward)
- Rent affordability thresholds
- Displacement status (based on rent affordability and eviction risk)

ProspectiveMover: Prospective movers represent external households considering moving into the study area. These agents begin outside the model area and are drawn from a distribution representative of the broader middle-class population of Cape Town. Their primary function is to evaluate vacant housing units within patches based on rent affordability and environmental livability. If a vacant unit meets their criteria, a prospective mover transitions into becoming a resident household, occupying the housing unit and updating the occupancy status of the respective patch.

Properties associated with prospective movers:

- Income distribution (higher median than incumbents)
- Criteria for housing choice (livability score and rent affordability)

Nature-Based Solutions (NbS) as Objects: NbS interventions such as community parks are scenario-based events rather than active agents. Their introduction is modeled by directly altering the environmental attributes of specific patches. Upon rollout, NbS significantly increase the environmental livability score, subsequently influencing the local housing market dynamics by making the area more attractive and potentially increasing rent values. This modeling approach facilitates the assessment of NbS impacts on displacement and the distribution of benefits across socio-economic groups.

Additional model infrastructure includes a scheduler, activating agents sequentially each time step, and global parameters that define rent changes, livability adjustments, and eviction risk calculations. These global parameters and mechanisms are detailed further in the Modeling Equations section in Appendix A.

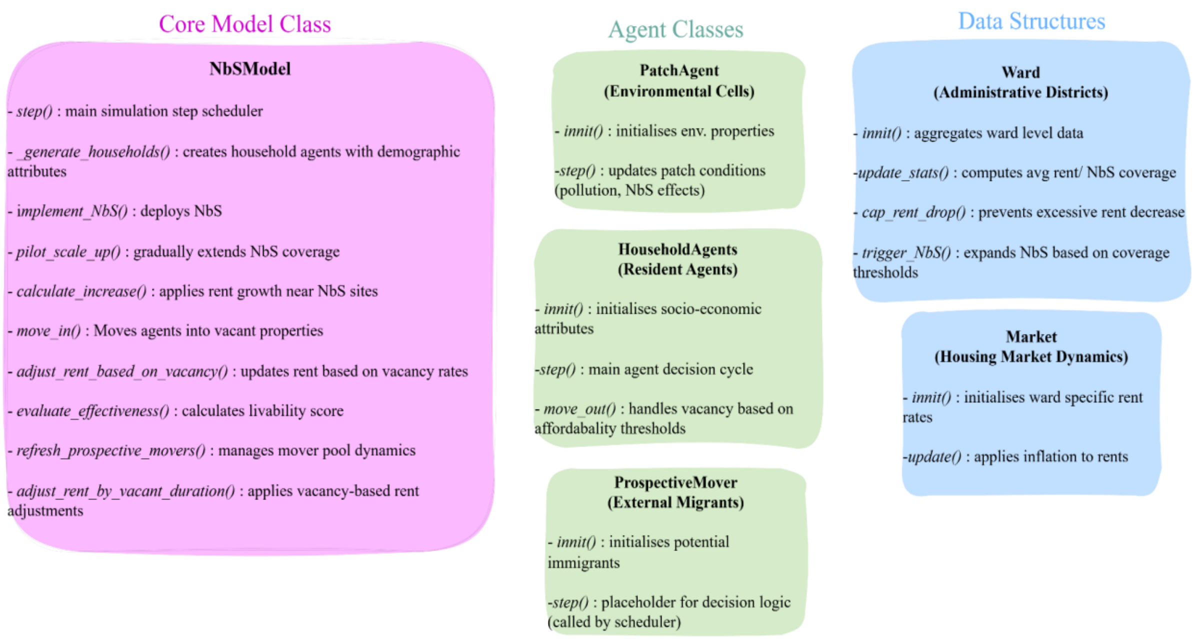


Figure 3: ABM Architecture Overview

3.3.2 Spatial Grid Setup

The simulation environment is represented as a 2D grid composed of 100m x 100m patches covering the geographic boundaries of Cape Town electoral Wards 57 and 79. This spatial representation was generated using electoral ward boundaries and demographic data from the 2011 South African Census, integrated into a unified GIS dataset within QGIS software. The selected resolution of 100m x 100m patches was chosen as a practical balance between detail and computational manageability, allowing sufficient granularity to capture local neighbourhood variations while remaining computationally efficient.

However, this spatial resolution presents potential limitations, notably border effects. Border effects can lead to unusual modeling outcomes, such as the underestimation of spillover effects or inaccurate representations of neighbourhood dynamics near the grid edges. For example, rent changes triggered by NbS improvements on boundary patches might not fully propagate to neighboring patches outside the modeled area, thereby distorting the perceived attractiveness and livability of edge areas. Similarly, households located at the borders might face unrealistic rent dynamics or displacement pressures due to truncated neighbourhood interactions. These potential limitations are carefully considered in the modeling process by explicitly including spillover mechanisms that attempt to minimize artificial boundary effects, ensuring neighboring patches within the model receive appropriate influences to accurately simulate realistic environmental and housing market conditions.

3.3.3 Resolution and Scale

Spatial and temporal resolution define the granularity of an agent-based model in space and time. This resolution "grain" allows the model to capture fine-grained urban features and local heterogeneity, aligning the grid cells with roughly a city block or small neighbourhood parcel. Choosing an appropriate spatial resolution is critical for representing the processes of interest: the resolution should be fit to the real-world phenomena's scale (Manson et al., 2020). For instance, one land-use ABM initially used 30 m cells and considered coarser grids up to 200 m, determining resolution based on the minimum area over which decisions are made and the scale at which key processes occur (Parker et al., 2002). In the present context, 100 m cells provide a detailed canvas to model micro-level changes in green amenities and housing at the neighbourhood scale, without averaging away important spatial variations.

Temporal resolution denotes the model's time step, the interval at which agent decisions and state updates occur. The model operates with a monthly time step, meaning that the state of the system is updated every month. An equal-step temporal framework (as opposed to event-driven timing) is common in ABMs for its conceptual simplicity, but it requires carefully selecting a step size that captures the dynamics of interest (Manson et al., 2020). A one-month interval was chosen to balance detail with tractability: monthly steps are fine-grained enough to reflect gradual socio-environmental changes (e.g. household relocation, incremental green infrastructure growth) that would be lost with yearly steps, yet they avoid the computational burden and data demands of daily steps. Monthly timing also aligns with many urban processes – for example, housing and rental markets often operate on a monthly cycle, with rents due monthly and tenants typically making relocation decisions on that timeline (Babakan & Alimohammadi, 2015). Using a monthly increment allows the model to simulate multi-year dynamics of green gentrification while capturing season-to-season and month-to-month variations in population, housing prices, and environmental conditions. The general scale of green gentrification is 3 to 10 years (Anguelovski et al., 2019; Immergluck & Balan, 2017) but month to month changes in housing prices and demographic composition are observable in the model which runs over 10 years.

In summary, the model's spatial resolution (100 m grid) and temporal resolution (monthly steps) are designed to support a spatio-temporal scale consistent with the phenomenon of green gentrification. Theory and prior studies emphasize that matching the model resolution to the scale of decision-making and interactions is essential for realism (Manson et al., 2020). The 100 m cells can represent block-level environmental features and displacement events, which is important because gentrification often unfolds at a micro-neighbourhood scale with strong spatial externalities (O'Sullivan, 2020). Likewise, monthly increments allow agents and environmental variables to evolve in sync with real-world urban change rhythms. These resolution choices enable the simulation to capture micro-level displacement and environmental dynamics (such as localized rent increases near new green spaces, or gradual improvements in vegetation cover) that drive the broader patterns of green gentrification.

3.4 Model Assumptions and Equations

3.4.1 Model Design Assumptions

Agent-based models (ABMs) inherently involve simplifying assumptions to facilitate tractable and focused analyses of complex social-environmental systems (Epstein, 2006; Grimm et al., 2010). Clearly stated assumptions help define the scope of the simulation, providing a transparent rationale for model design choices and simplifying real-world dynamics into manageable elements for computational representation (Gilbert & Troitzsch, 2005). The following assumptions outline essential simplifications made in this model to investigate displacement dynamics driven by the implementation of Nature-Based Solutions (NbS) in Cape Town.

Full initial occupancy**:** All housing units are assumed to be occupied at model start (zero vacancy). This eliminates unused units so that every relocation or vacancy triggers direct displacement, focusing analysis on rent pressures rather than vacancy dynamics. It reflects Cape Town's tight rental market, recent surveys show near-zero vacancy (e.g. ~1.07% in Western Cape, Q3 2024) (Known Magazine, 2024) justifying an initial 100% occupancy for the purpose of displacement modeling.

Uniform spatial distribution: Households are placed evenly across the spatial grid with no initial clustering. This neutral baseline avoids introducing artificial hotspots or biases into the simulation. By starting from a homogeneous distribution, any emergent spatial patterns in displacement can be attributed to model dynamics (e.g. proximity to NbS) rather than pre-existing conditions, simplifying interpretation under limited fine-scale data.

All households are renters: The model treats every household as a renter (no homeowners) (Binner & Brett, 2018). This is a simplification in housing market modeling that focuses on rent-based displacement (Immergluck & Balan, 2017). Renters are most susceptible to market-driven displacement, whereas homeowners would instead accrue equity gains from rising property values (Binner & Brett, 2018). Given Cape Town's large renter population and the short-term focus of the model, excluding ownership simplifies the tenure dynamics and concentrates on rental market pressures.

Modelled Agents: The model explicitly focuses only on two types of agents: renters and landlords, although landlord behaviour is represented implicitly rather than explicitly. Renters' decision-making regarding housing choices is modelled through a simplified, utilitarian function primarily driven by affordability and immediate availability, without detailed behavioural considerations such as personal preferences, social networks, or emotional attachments. Landlord behaviour, meanwhile, does not include interactive elements, such as coordination among landlords to adjust rental prices collectively during periods of high vacancy. Furthermore, the model excludes other potentially influential agents, such as citizen unions or community advocacy groups. Such agents could feasibly respond to rising rents or neighbourhood changes by collective mobilisation or resistance against NbS implementation. This simplification results in a limited feedback loop, as illustrated in Figure 4, whereby real-world feedback from community responses to NbS projects is not captured within the simulation. Consequently, the model inherently constrains the agency of represented stakeholders, reflecting a stylised methodological choice designed both to facilitate computational tractability and to accommodate the current absence of detailed behavioural data required for richer agent interactions.

Fixed housing stock: The total number of housing units (patches) is held constant throughout the simulation (no new construction or demolition) (Binner & Brett, 2018). This reflects the inelasticity of housing supply in the short term; most models assume that existing stock cannot quickly expand with changing conditions (Binner & Brett, 2018). Holding supply fixed ensures that any increase in housing demand (from NbS effects) directly translates into price and rent pressure, isolating displacement effects from supply-side changes.

Exogenous NbS scenarios: Nature-based solutions (green infrastructure projects, etc.) are introduced exogenously according to predefined scenarios, rather than resulting from agents' choices. In other words, NbS locations and extents are fixed inputs to the model (e.g. city-planned interventions), not determined within the simulation. This assumption aligns with the research goal of evaluating specified NbS deployments and isolates their impacts on the housing market without modeling the (complex) process of NbS adoption or planning by agents.

Income-based displacement threshold: A household is flagged as displaced if its rent burden exceeds a set affordability threshold (e.g. 30% of income). The 30% rule is a widely used standard for housing affordability and rent stress (Herbert, Hermann, & McCue, 2018). By using this criterion, the model assumes that when rent outpaces affordability, the household must relocate. This ties displacement directly to local income levels and captures the idea that higher rents (for example, due to nearby NbS improvements) will force low-income renters out once they can no longer "afford" their housing.

Unlimited higher-income in-movers: The model assumes an effectively unlimited supply of prospective renters with incomes above the local population. In other words, wealthy outsiders can always be attracted into the market. This creates constant upward pressure on demand for improved housing (e.g. near NbS areas) and ensures that rent increases are not limited by lack of demand. In the real world, the assumption of an unlimited supply of higher-income in-movers can be seen as a stylized exaggeration, but it reflects patterns observed in many rapidly gentrifying cities. For example, in Cape Town, high-income professionals—often from other parts of South Africa or abroad—are drawn to neighbourhoods near environmental upgrades like the Liesbeek River Trail or the planned River Club development. These newcomers consistently outbid existing residents for housing, especially near new green amenities, contributing to sustained upward pressure on rents (Parnell & Pieterse, 2010; Visser & Kotze, 2008). Similarly, in cities like New York or London, even after decades of gentrification, demand from wealthier outsiders remains high in neighbourhoods near parks or waterfront redevelopment

(Anguelovski et al., 2019; Gould & Lewis, 2017). Thus, this assumption serves to stress-test displacement mechanisms by modeling a persistent influx of high-income renters in areas enhanced by NbS.

No policy interventions: The simulation excludes any policy measures (e.g. rent control, housing subsidies, inclusionary zoning) for the basecase scenario. This pure-market scenario isolates the causal chain from NbS to prices to displacement without confounding effects of government or institutional actions. It provides a baseline "unregulated" outcome; subsequent policy analyses have been built on this scenario. This assumption reflects the research focus on natural market responses to NbS in Cape Town, independent of policy safeguards.

3.5 Parameter Justifications

All parameter values are chosen to match Cape Town conditions or literature values:

Initial rent (Ward 57: ~R250/m²; Ward 79: ~R75/m²)**:** Rents are calibrated to local data. For example, a one-bedroom flat in Woodstock (Ward 57) rents for roughly R8,000/month (~30 m²), about R250/m² (Seeff Property Group, 2018). By contrast, rentals in Mitchell's Plain (Ward 79) can be on the order of R1,500/month for a modest room (≈20 m²), about R75/m² (via local housing websites). The model uses these ward-level values as starting rents.

Rent growth ~5% per year: This rate is based on observed long-term trends. South African rents rose about 45.8% over a decade (2014–2024), implying ~4.6% annual growth on average (Thorne, 2025). Rounded to ~5% to capture ongoing inflationary pressure in the rental market.

Household income growth 0–2% per year. South Africa's recent income growth has been very low (around 1% per year) (Development Policy Research Unit, 2024), often trailing inflation. We therefore assume nominal income growth in the range 0–2% per annum, reflecting historical stagnation.

Rent caps (Ward 79: R150/m²; Ward 57: R300–400/m²): To prevent unbounded rent escalation, the model imposes ceiling rents roughly 2–3× above initial levels. For example, R150/m² (Ward 79 cap) is about double the initial R75/m², and R300–400/m² (Ward 57 cap) slightly above the initial ≈R250/m². These caps are consistent with the upper end of current rents in each ward.

NbS spillover with exponential distance decay. The benefit of an NbS (e.g. a park) is assumed to decline exponentially with distance from it. This is a standard spatial decay function (following Tobler's law) used in spatial-interaction models (Azad et al., 2024). In practice, a household's perceived amenity gain from an NbS located d meters away is proportional to $\exp(-\beta d)$ (equations are detailed in the Appendix A).

Livability via environmental quality: "Livability" in the model is defined in terms of environmental conditions (green space, air quality, etc.). This follows urban planning definitions that place environmental quality at the core of neighbourhood livability. In effect, patches with higher environmental quality scores are considered more desirable.

3.6 Model Behavior

3.6.1 ABM Decision Logic

Each household agent has an income (annual earnings) and faces a rent payment for its dwelling. Affordability is evaluated by comparing income to rent. Consistent with common housing practice, a rule-of-thumb threshold is used (for example, rent not exceeding 30% of income at model initialisation) (Pagani et al., 2022). Concretely, the model checks whether annual household resources are at least one-third of the annual rent; if not, the dwelling becomes unaffordable (Pagani et al., 2022).

If rent exceeds affordability (for example, due to rising rents or an income shock), the household must either relocate or is effectively evicted. An eviction (or unaffordability event) frees up the dwelling (making it vacant) and forces the household to seek cheaper housing. Likewise, households periodically reassess satisfaction with their current home: if a household's expected satisfaction (based on dwelling features and neighbourhood quality) falls below that of an alternative, the agent voluntarily moves. In either case, moving means the agent searches available vacant units (within the same ward or beyond, depending on model rules) that meet their needs (cost, space, amenities). When an agent leaves, the now-vacant dwelling is made available in the market. This is how an eviction threshold has been established in the model, it is purely based on economic resources and does not take into account other social or environmental pressures which might propel or force people to relocate. This limitation and its consequences along with further ideas to make the research more robust have been detailed in the later sections of this thesis.

Households compete indirectly for limited housing stock. An occupied dwelling is unavailable to others; high demand means vacancies are scarce. As one model identified, occupying a space prevents other similar agents from finding a vacancy in that spatial orientation, which eventually forces them to leave (Pagani et al., 2022). In the simulation of this study, if many agents vie for few vacant units, some agents remain un-housed or are forced to exit the market (simulating, e.g., out-migration). Agents' moves thus create vacancy chains: when one household moves out, another may take its place if affordable, and so on. This competition for dwellings is the primary form of agent interaction. Through these decisions and interactions, households collectively drive market dynamics: aggregate affordability, eviction rates, and relocation patterns emerge from the micro-level decision rules. The agents (households) interact more directly with their environments compared to each other.

3.6.2 Core Dynamics

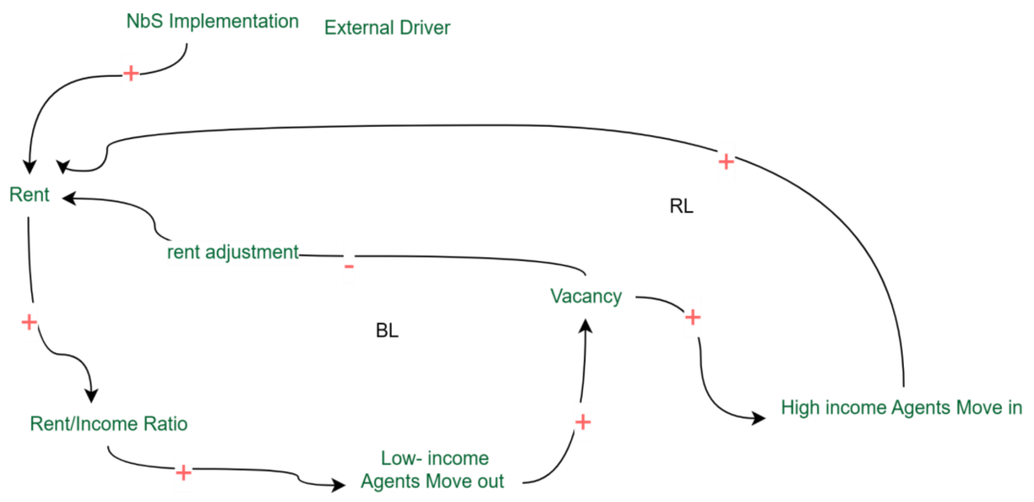


Figure 4: Core Model Mechanics

- Rental Dynamics: Rents in each ward evolve over time based on demand and supply conditions. Conceptually, rent in the next period increases when demand (driven by population/income growth or low vacancy) is high, and decreases when supply is abundant. In the model, landlords adjust rent to cover costs and market conditions: for example, if vacancy is low (high demand), rents rise; if many units are vacant, rents are lowered to attract tenants. Similarly, if landlords face higher financing costs (e.g. rising interest rates), they may raise rents to cover these expenses (Gamal et al., 2024). Income growth also plays a role: as households become wealthier, their willingness and ability to pay increases, which can push rents up in line with historical inflation or observed trends.

- Vacancy Dynamics: Vacancies arise exclusively when households are evicted. At each time step, one or more dwellings may become vacant due to eviction events. These units are then immediately made available on the rental market and can be filled by waiting households or new entrants whose affordability and location preferences align with the available dwelling. If no suitable agent is available—either due to income constraints or lack of interest—the unit remains vacant and is reconsidered in subsequent steps. In some cases, especially in wards with lower livability or poor rent-to-income ratios, units may remain unoccupied across multiple time steps. The model tracks the vacancy rate in each ward, which is typically low to reflect observed urban conditions, but can temporarily rise under certain stress scenarios. Importantly, the vacancy rate feeds directly into rent dynamics: high vacancy exerts downward pressure on rents, while low vacancy leads to upward pressure (Gamal et al., 2024). This vacancy-fill mechanism closes the loop in the displacement cycle: evictions create vacancies, and those vacancies are filled—when possible—by eligible agents, or otherwise persist until conditions change.

In designing these model components, certain assumptions have been made, care has been taken to align the core assumptions with both existing modelling theory and empirical evidence when available. Some assumptions are explained here and can be found in more detail in the simulation configuration section and Appendix A.

Using a logistic eviction function captures the non-linear risk of displacement as affordability declines:

$$risk = \frac{1}{1 + exp(-slope\ x\ (ratio\ - thr))}$$

where *slope* and *scale* are ward-specific parameters and *thr* is the model's eviction threshold.

The exponential decay for spillover rent increases is grounded in urban economic theory that amenities' influence decays with distance (Pandit, Polyakov, & Sadler, 2013):

$$spill\ = \alpha\ x\ (1 - e^{-\gamma d}),$$

Where α and γ depend on the ward. Each household in the neighbourhood increases rent by this fraction:

$$r_{new} = r_{old} + min(spill, 0.20)\ x\ r_{old}$$

The parameter variations by ward reflect that not all neighbourhoods react identically to greening (some might see widespread gentrification, others very localized).

A rent increase delay was included to simulate policy interventions (like temporary rent control or phasing of projects) further analyses can test if a 4-month delay is enough to significantly change outcomes versus, say, no delay. The 2% direct rent uplift and ~5% maximum spillover were chosen as plausible small effects; they can be adjusted if calibration against real cases suggests different magnitudes, but they provide an initial scenario to explore.

The vacancy rent discount mechanism is an important equilibrium device, preventing indefinite accumulation of vacancies (landlords will eventually adjust), its piecewise linear form was chosen for simplicity yet flexibility to model different market tightness:

Each ward has vacancy-rate thresholds (LOW, HIGH) and corresponding maximum penalties (MAX_LOW, MAX_HIGH). Let v be the fraction of units vacant in the ward. The one-time penalty (discount) applied when a unit is re-rented is:

$$\text{penalty(v)} = \begin{cases} v\ x\ \frac{MAX\_LOW}{LOW}, & v \leq LOW \\ MAX\_LOW + \frac{v - LOW}{HIGH - LOW}\ x\ (MAX\_HIGH - MAX\_LOW), & LOW < v \leq HIGH \\ MAX\_HIGH, & v > HIGH \end{cases}$$

Chapter 4: Model Implementation

This chapter provides a comprehensive account of the Agent-Based Model (ABM) developed to investigate the socio-economic impacts of Nature-Based Solutions (NbS) in Cape Town. The following sections will detail the model's empirical foundations, its initial state configuration, the parameters governing its dynamics, and its underlying technical architecture. This detailed description is intended to provide a transparent and replicable overview of the computational tool used in this research.

4.1 Data Sources and Calibration

To ensure the model is a credible representation of the study area, its environment, agents, and parameters are empirically grounded in data specific to Cape Town. The parameterization process involved both direct estimation from available data and an iterative calibration procedure to align model behavior with observed real-world patterns.

4.1.1 Data Sources

The model integrates three principal categories of data to construct its initial state and define its operational boundaries:

4.1.1.1 Demographic and Housing Data

The primary source for populating the model is the 2011 South African Census. This dataset provided detailed, ward-level statistics on population counts, household sizes, income distributions (disaggregated by racial group), dwelling counts, and racial composition. This information was indispensable for initializing the attributes of HouseholdAgents, ensuring the synthetic population accurately reflects the statistical distributions and socio-spatial segregation patterns of Cape Town's actual population.

4.1.1.2 Geospatial Data

The model's spatial environment was constructed using Geographic Information System (GIS) data, including official municipal ward boundaries and land use layers. These data were processed in QGIS and then integrated into the model via a custom function (prepare_capetown_grid), which generates a grid of patches corresponding to the geographic layout of the study area. Each patch in the grid is assigned a ward_id, linking it to its corresponding census data and ensuring the model's spatial structure reflects the city's administrative geography.

4.1.1.3 Economic and Market Data

To establish a realistic economic baseline, initial rent levels were benchmarked against local rental market statistics and municipal reports. While granular rent data for every patch is not available, the model approximates a realistic rent gradient by calculating a baseline rent-per-square-meter for each ward as a function of its median income. This links housing costs to local affordability. The model also incorporates a baseline annual rent inflation rate of 5%, a figure broadly consistent with moderate housing inflation in many urban centers, to represent exogenous market pressures that affect all residents.

4.1.2 Model Calibration

The model's parameters were defined using a dual approach of direct estimation and iterative calibration, a common practice in ABM development (Parker et al., 2003).

4.1.2.1 Direct Parameter Estimation

Several parameters were set directly from data or established economic benchmarks. For example, the annual household income growth rate was set to a modest 1% to reflect the near-stagnation of real income growth observed in South Africa. The initial number of households per ward, their racial composition, and income distributions were also directly populated from census data to establish a realistic starting point.

4.1.2.2 Iterative Calibration and Validation

Many behavioral parameters such as the precise thresholds for mobility, the sensitivity of eviction risk to rent burden, or the magnitude of rent uplifts from NbS are not directly observable. These were calibrated by running the model iteratively and systematically adjusting their values until the model's macro-level outputs aligned with known empirical benchmarks. For instance, the parameters of the logistic eviction function were tuned to produce a baseline annual housing turnover rate of approximately 5–15%, a range consistent with typical urban rental market churn. Similarly, the model's rent dynamics were adjusted so that the simulated average rent growth in a no-NbS control scenario closely matched historical rent trends in the respective wards. This process ensures that the model's emergent behavior is plausible and grounded in observed reality.

To ensure that the research findings are robust, sensitivity analyses were conducted for the eviction threshold. The eviction risk thresholds were systematically varied to confirm that the model's core conclusions about displacement are not overly dependent on it.

4.1.3 Model Initialisation

The simulation begins by constructing a detailed digital representation of the study area's physical environment and its population of households. This initialization process is critical for ensuring the model starts from a realistic baseline that accurately reflects the known demographic, economic, and housing conditions of Cape Town before any interventions are simulated.

4.1.3.1 Spatial Environment: Patches and Wards

The model's environment is a two-dimensional grid, managed by the MultiGrid class from the Mesa library, which allows multiple agents to occupy the same cell. This grid is populated by stationary PatchAgent instances, each representing a discrete spatial unit.

- PatchAgent Attributes: Each patch encapsulates the local environmental and social characteristics of its location. Key attributes defined in the PatchAgent class include:
    - ward_id: The municipal ward the patch belongs to, inherited from the integrated GIS data.
    - pos: The (x, y) coordinates of the patch on the grid.

- Environmental Qualities: pollution_index and heat_level, initialized with integer values between 0 and 9 to represent baseline heterogeneity in environmental conditions across the urban landscape.
- NbS Attributes: NbS_implemented (a boolean flag, initially False for most patches), NbS_tick (the timestep of implementation), and NbS_percentage (a float representing the patch's potential for greening).
- Housing and Rent Dynamics: initial_households (the number of households on the patch at t=0), rent_update_delay (a boolean to manage the timing of rent increases), and a dynamic livability score.

At startup, a small fraction (5%) of patches with the highest NbS_percentage are selected as initial pilot sites for greening. For these patches, the NbS_implemented flag is set to True, and their NbS_tick is recorded as 0. This establishes the initial footprint of the NbS intervention.

4.1.3.2 Population and Housing Market

The grid is populated with HouseholdAgents, the central actors representing resident households.

- HouseholdAgent Attributes: Each household is characterised by a set of socio-economic and status attributes:
    1. Socio-economic Profile: income, rent, race, and size (household size).
    2. Status Flags: A boolean vacant flag indicates if the housing unit is occupied. The vacant_since and vacant_duration attributes track the timing and length of vacancies, which is crucial for market adjustment mechanisms. The origin attribute distinguishes original "local" residents from "external" newcomers who move in during the simulation.
    3. Location: pos (the patch it occupies) and ward_id (inherited from the patch).

- Household Generation Process: The _generate_households method orchestrates the creation and placement of households:
    1. The total number of households for each ward is taken from census data.
    2. For each household to be created on a patch, a race is assigned probabilistically using numpy.random.choice. The probabilities are drawn directly from the ward's racial composition percentages (e.g., Black African , coloured, white) stored in the patch's data record.
    3. A household's income is then drawn from a normal distribution. The mean of this distribution is the median income for that specific race in that specific ward, as per census data, with a standard deviation set to 20-25% of the mean to create realistic income variance within socio-economic groups. A minimum income is enforced to avoid non-viable agents.
    4. Household size is sampled from a ward-specific distribution. This reflects observed demographic patterns; for instance, the high-income Ward 57 is initialized with smaller households on average, while the lower-income Ward 79 is assigned larger households.
    5. Finally, the initial rent for the household is calculated based on its size and the ward's prevailing rent-per-square-meter rate, ensuring that larger units are more expensive.

- Market Agent and Rent Initialization: A single Market object is created to manage exogenous rent dynamics. It is initialized with the baseline rent-per-square-meter for each ward and an annual inflation rate of 5%. At each monthly tick, it updates its rates by a monthly_factor, causing a gradual increase in housing costs for all tenants across the simulation, independent of any NbS effects. This captures the background trend of rising living costs.

- Prospective Movers: To simulate in-migration and the filling of vacant units, the model initializes a pool of ProspectiveMover agents. The initial size of this pool is set to be a substantial fraction of the total resident population (e.g., one-fifth of total households) to ensure a ready supply of potential tenants. The demographic attributes (income, race) of these movers are sampled based on the overall distribution of households across all wards, creating a realistic cross-section of potential newcomers who might be attracted to newly available housing.

4.1.3.3 Simulation Configuration and Parameter Justification

The model is configured to run simulations where each tick represents one month, for a duration of 120 months (10 years). This timescale is sufficient to capture medium-term gentrification processes that unfold over several years. The sequence of events within each tick is fixed to ensure logical causality: market inflation is applied, NbS rent delays are checked and increases triggered, households probabilistically decide on move-outs, prospective movers are refreshed, vacant units are filled by new households, and livability scores are evaluated. The parameters governing these dynamics are critical to the model's behavior.

Table 1. Key Model Parameters for Simulation, with Justification

Parameter	Value	Description and Rationale
Rent delay after NbS	rent_delay_ticks = 4	Defines a 4-month grace period between the implementation of an NbS and any associated rent increase. This simulates policies like temporary rent freezes or the natural lag in market response, giving incumbents a brief window to enjoy the amenity benefits before costs rise. The 4-month duration was chosen to align with typical lease renewal periods.

Rent increase from NbS spillover	Function: $$s(d) = \alpha \, x \, (1 - e^{-\gamma d})$$ Ward 57: α=0.03, γ=0.20 Ward 79: α=0.10, γ=0.05 $s(d)$: *NbS spillover at distance d* α: *maximum uplift (asymptotic)* γ: *spatial decay constant*	Models the spatial spillover effect, where the rent of patches neighboring an NbS site also increases, with the effect decaying with distance d. The exponential decay form is grounded in urban economic theory and empirical studies showing that amenity effects diminish with distance. The ward-specific parameters (alpha, gamma) test different gentrification scenarios: Ward 57 (wealthier) is modeled with low-impact, highly localized spillover, while Ward 79 (lower-income) has broader, more significant potential rent impacts, reflecting how greening might trigger different spatial patterns of gentrification. This function increases with distance, saturating at α.
Eviction Risk Function	Logistic Function: $$P_{evict} = \frac{1}{1 + e^{-slope.(ratio - threshold)}} \, x \, scale$$ ratio: current rent divided by income threshold: the stress level above which eviction becomes likely slope: steepness of the curve scale: dampens the probability after sigmoid calculation	Eviction risk is modeled as a probabilistic outcome based on a household's rent-to-income ratio (ratio). The logistic function provides a smooth, non-linear escalation of risk, which is more realistic than a hard cutoff and is common in housing research. The ward-specific parameters reflect differing levels of housing stability and landlord behavior. This captures that the probability of eviction increases rapidly as the rent/income ratio exceeds a threshold.

Vacancy-Induced Rent Adjustment	Piecewise linear function based on ward vacancy rate ν Rent inflation modifier: $R_{\nu} = \{MAX_{Low}, if\ \nu < \nu_{min}\}$ $R_{\nu} = \{linear\ increase, if\ \nu_{min} \leq \nu \leq \nu_{max}\}$ $R_{\nu} = \{MAX_{HIGH}, if\ \nu > \nu_{max}\}$	This mechanism introduces a one-time rent discount for new tenants based on the ward's vacancy rate, simulating landlords lowering prices to attract tenants in a soft market. The discount is calculated using a piecewise linear function based on the ward's vacancy rate, with different maximum penalties (MAX_LOW, MAX_HIGH) for different wards. The affluent Ward 57 has very small discounts, representing a "tight" market where landlords are reluctant to drop prices, while Ward 79 is more responsive. This provides a crucial market-stabilizing feedback loop.
Annual Income Growth	annual_income_growth = 0.005 (0.5%)	This parameter applies a uniform, 0.5% annual growth rate to all household incomes, translated into a monthly factor (monthly_income_factor). This modest rate reflects that real household incomes in South Africa have been nearly flat. It creates a key dynamic: if the annual rent inflation outpaces this income growth, households become increasingly rent-burdened over time, a primary driver of displacement even in the absence of NbS.
NbS Rollout and Expansion	Initial pilot: 5% of all patches $G_0 = 0.05.N$ Where N is the number of patches Scale up phase: Every 6 months, 8 new patches are greened $G(t) = G_0 + 8\,x\,[\frac{t}{6}]$	The simulation begins with a 5% pilot program, targeting patches with the highest greening potential. This represents a limited, targeted initial investment. Subsequently, the pilot_scale_up function simulates a gradual expansion by greening an additional 8 patches every 6 months. This models a phased rollout where successful

pilots are incrementally scaled up, leading to a steady but not instantaneous transformation of the green landscape in targeted areas.

4.2 Data Collection and Metrics

Throughout the simulation, multiple metrics are collected at each time step, but the following are the most fundamental ones which have informed the results.

4.2.1 Displacement Counts

The model logs every move-out event, recording the displaced household's attributes, including race and income. These event-level data are aggregated into key measures, such as the total number of displacements over time and detailed breakdowns by socio-demographic groups. For each ward, a computation is performed to determine how many households of each racial group were displaced by the end of the simulation run. This directly addresses the research question of who is being displaced by greening initiatives. A primary metric for analysis is the displacement rate, calculated by race for pilot versus non-pilot areas (e.g., the percentage of Black African households in a greening ward that moved out compared to the percentage in a non-greening ward). An elevated displacement rate in greening wards serves as a quantitative indicator of green gentrification occurring along racial lines.

4.2.2 In-mover Characteristics

Similarly, for every move-in event, the model tracks the race and income of the newcomers. This allows for a comparison between the characteristics of new residents and the original residents they replace. A metric of significant interest is the change in the proportion of specific racial groups, such as White households, within a ward from the beginning to the end of the simulation; a notable rise would suggest racial gentrification. The analysis also involves measuring the average income of new movers against that of the households they displaced to quantify the degree of economic upgrading or class-based gentrification. These statistics are compiled for each experimental scenario to enable robust comparisons.

4.2.3 Rent Trajectories

The average rent for each ward is recorded at every time step. This time-series data allows for the plotting of rent inflation curves and the identification of divergence between different wards or scenarios. Should NbS interventions cause accelerated rent growth, the rent trajectories of pilot wards are expected to slope upward more steeply than those of control wards. Rent-to-income ratios are also tracked over time for different groups to assess affordability pressures. An analysis of whether the rent burden of the lowest-income quartile in a greening area increases relative to the baseline is particularly telling. By logging each agent's rent and income, the model facilitates an analysis of distributional effects, such as whether greening exacerbates inequality in housing costs.

Chapter 5: Scenario Definitions

This chapter conceptualises three scenarios based on development plans released by the City Council of Cape Town (CoCT, 2018) and details how they were operationalised in code, answering sub-research question 2 and 3.

5.1 Baseline Scenario

The Base Scenario represents the default conditions of the agent-based model in which Nature-based Solutions (NbS) are incrementally introduced without accompanying protective housing policies or interventions. This scenario reflects the typical pattern observed in urban contexts where green infrastructure investments improve local environmental conditions and increase neighbourhood attractiveness, leading to higher property values and subsequent displacement pressures. The primary aim of simulating this baseline scenario is to capture the underlying socio-economic dynamics triggered by NbS implementation alone, allowing for subsequent comparison to scenarios with targeted interventions.

The conceptual motivation for this baseline lies in accurately understanding the unmitigated displacement effects associated with urban greening strategies. In Cape Town's context, the absence of proactive housing protection or subsidy mechanisms frequently leads to increased displacement risk among vulnerable populations, potentially exacerbating socio-economic inequalities and undermining broader social sustainability objectives (City of Cape Town [CoCT], 2018).

5.2 Scenario 1: Inclusionary Housing

Inclusionary housing is a planning mechanism designed to integrate affordable housing units within market-rate residential developments. Scenario 1 is directly inspired by CoCT's draft Inclusionary Housing Policy, which explicitly encourages developers to incorporate affordable units into well-located urban areas undergoing significant upgrades (CoCT, 2018). The rationale behind this scenario is to leverage NbS projects—such as community gardens and green roofs—as anchors for equitable urban regeneration. By coupling NbS interventions with mandatory inclusionary housing provisions, this scenario seeks to preserve socio-economic diversity, ensuring low-income residents have continued access to improved neighbourhood conditions without displacement.

Inclusionary housing is recognized in international contexts as an effective policy instrument for mitigating displacement and fostering mixed-income communities (Calavita & Mallach, 2009). In Cape Town, the strategic coupling of inclusionary housing with NbS is particularly valuable given the historical spatial inequalities and affordability pressures in desirable urban locations.

The scenario is operationalised within the agent-based model explicitly through modifications to household allocation logic in the move_in() function:

1. Reservation of Housing Units:
    - A fixed proportion (inclusionary_fraction = 0.50) of all newly available housing units are reserved for low-income households (those earning below 50% of local median income).

2. Rent Discounts for Low-income Households:
    - Qualifying households benefit from significantly reduced rents (inclusionary_discount = 0.60, implying a 40% rent reduction).
    - Eligible low-income movers are identified through ward-specific median income thresholds (local_income_cutoff_by_ward).

This logic ensures prioritized and affordable access for low-income agents, directly mitigating displacement risks associated with NbS-driven rent escalation.

5.3 Scenario 2: Targeted Rent Subsidies on NbS Patches

Scenario 2 aligns conceptually with CoCT's equitable housing objectives, which highlight the necessity of subsidised rental policies to maintain housing affordability (CoCT, 2018). Although not explicitly articulated as city policy specifically for NbS zones, the concept complements existing municipal objectives of protecting lower-income households from market-induced displacement. The targeted rent subsidy is spatially precise, directly benefiting households proximate to newly implemented NbS interventions. This targeted approach is validated by international research demonstrating that carefully directed subsidies effectively mitigate gentrification impacts by directly addressing affordability gaps created by localised property value increases (Rigolon & Németh, 2018).

The targeted rent subsidy scenario is operationalised using a dual mechanism:

- Direct Rent Subsidies (Temporary Discounts):
    - Upon NbS implementation, households within an 800-meter radius are granted a temporary 20% rent discount (discount_rate = 0.20) lasting 60 simulation steps.
    - Households revert to original rents (base_rent) post-subsidy period, ensuring a temporary yet significant relief from immediate market pressures.

- Indirect Eviction Risk Reduction:
    - Additionally, households directly located on NbS-enhanced patches benefit from a reduced eviction probability (environment_factor = 0.85, implying a 15% risk reduction).
    - This modification is embedded directly within the eviction calculation function (HouseholdAgent.move_out()).

These three scenarios were strategically selected based on their alignment with CoCT's existing and emerging housing equity policies and international evidence on effective mitigation strategies against green gentrification. Scenarios 1 and 2 specifically correspond to the city's actionable frameworks, making them suitable for direct implementation and empirical testing. Scenario 3, while remaining conceptual, extends the policy scope by highlighting a more robust but practically challenging solution, reflecting the critical discussions surrounding housing justice and long-term affordability. The scenario choices reflect an informed approach to urban policy design, systematically addressing both immediate displacement pressures and longer-term structural affordability through diverse yet complementary policy mechanisms.

Chapter 6: Model Simulation Results

This chapter presents the simulation outcomes for the Baseline, Scenario 1: Inclusionary Housing, and Scenario 2: Targeted Rent Subsidy, in a thematic manner. Rather than describing each scenario in isolation, the results are organized around four key themes that emerge from the model runs: housing affordability, residential displacement (by income and race), demographic change, and livability outcomes. This thematic structure highlights how different policy interventions influence various dimensions of urban equity and gentrification within the two wards in the city, which answers the research question: *"What are the distributional effects of the implemented NbS on different communities within Cape Town?"*.

Each section below describes what the corresponding figures show, interprets the differences across wards and scenarios, and discusses what these patterns suggest about broader dynamics of urban inequality in Cape Town.

6.1 Housing Affordability: Trends in Average Rents Over Time

6.1.1 Baseline Scenario

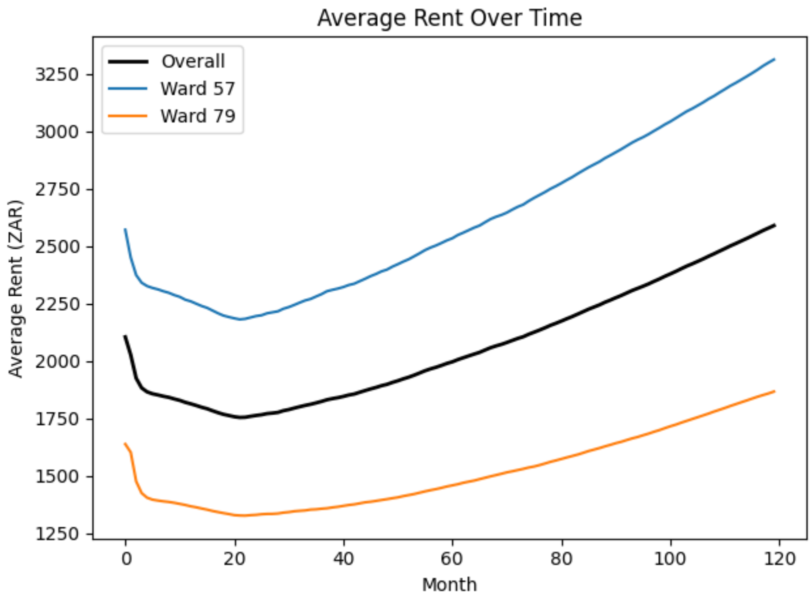


Figure 5: Avg Rent over Time for Basecase Scenario

Figure 5 illustrates the progression of average monthly rents citywide, alongside the specific trajectories for Ward 57 (Observatory) and Ward 79 (Mitchell's Plain), over a simulation period of ten years (120 months). The overall citywide trend indicates a consistent upward trajectory in rental costs, beginning from approximately R2,200 per month and reaching nearly R2,800 by the end of the simulation. This represents an approximate increase of 27% in average rents over the decade, indicating significant housing affordability challenges driven largely by market dynamics, sustained demand pressures, and annual rental inflation of around 5%.

A closer comparative examination of the rent trajectories in Ward 57 and Ward 79 reveals critical disparities reflective of local socioeconomic and spatial factors, including the implementation and influence of Nature-based Solutions (NbS). Ward 57, corresponding to the Observatory area and characterised by a higher initial average rent (around R2,600), experiences a notable increase over time, eventually surpassing R3,250. This increase of approximately 25% over the ten-year span can be attributed to several interconnected factors. Given Observatory's initial status as a higher-income neighbourhood, the carrying capacity for rental growth is substantial, allowing rents to escalate more significantly before confronting affordability constraints among the area's relatively affluent residents. Moreover, higher-income residents in Ward 57 likely demonstrate a stronger willingness to pay a premium for enhanced livability, including access to newly implemented green amenities and lower environmental stress indicators such as reduced heat and pollution levels. Furthermore, the neighbourhood's rent dynamics benefit substantially from spatial spillover effects resulting from localized NbS interventions, which amplify the attractiveness of adjacent areas. This cumulative cycle of increased demand and rising rents further attracts external movers who can sustain these elevated rental costs, compounding affordability pressures and accelerating the displacement risks faced by original residents.

Conversely, the rental landscape in Ward 79, representing the Mitchell’s Plain area, presents a different pattern. Initially starting at approximately R1,600, rents here see a relatively moderate rise, ending the simulation period at about R1,800—a total increase of roughly 12.5%. This can be explained by the neighbourhood's lower socioeconomic status, marked by households with comparatively limited incomes that constrain the extent of feasible rent escalation. In Mitchell’s Plain, even minor increases in rent carry significant affordability implications, making it difficult for rents to rise without rapidly exacerbating displacement pressures among existing residents.

Taken together, the pronounced disparity observed between these two wards underscores the inherent income inequality associated with market-driven urban transformations. The rapid rent increases in Ward 57 illustrate the tangible risks of implementing NbS and similar desirable urban amenities without accompanying regulatory measures such as rent controls or inclusionary housing provisions. In the absence of such safeguards, increasing rents disproportionately threaten lower-income residents, intensifying displacement pressures and reinforcing socio-spatial polarisation. Meanwhile, the comparatively slower rent increases in Ward 79 reflect a distinct yet related challenge: the potential for spatial inequalities to persist or even intensify, resulting from uneven distributions of environmental and infrastructural investments across neighbourhoods.

6.1.2 Scenario 1: Inclusionary Housing

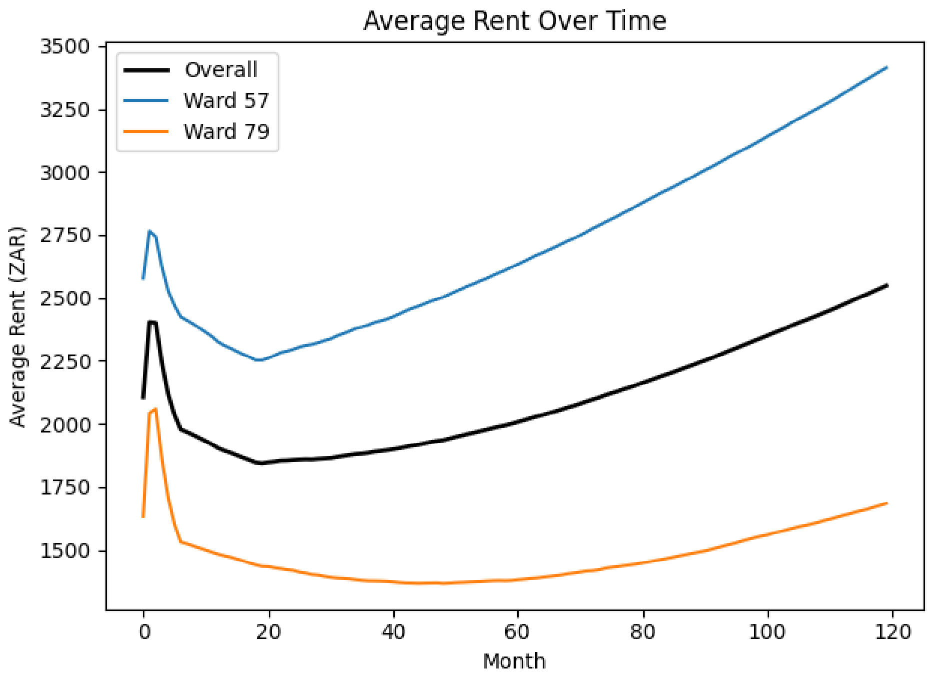


Figure 6: Avg Rent over Time for Scenario 1

This scenario integrates an inclusionary housing policy inspired by the City of Cape Town's draft Inclusionary Housing Policy, which requires residential developments in desirable and upgraded urban areas, which can be interpreted to include areas such as those receiving Nature-based Solutions (NbS) interventions—to reserve a portion of housing units as affordable options for low-income households. Specifically, 50% of available units are set aside for households earning less than half the local median income, with these eligible households receiving substantial rent discounts.

In this scenario, the citywide average rent begins around R2,200 per month, but demonstrates a more moderate trajectory compared to the baseline scenario, ultimately stabilizing around R2,600 by the end of the ten-year simulation, indicating an overall rent increase of about 18%. The initial rugged pattern arises from the immediate implementation effects of the inclusionary housing policy, whereby a large proportion of newly vacated or available units become reserved and subsequently occupied by lower-income households who qualify for substantial rent discounts. Such rapid, uneven unit turnover and the immediate enforcement of affordability measures create initial oscillations as the housing market adjusts dynamically, reflecting fluctuations in vacancies, move-ins, and temporary rent adjustments intended to stimulate occupancy.

Within Ward 57, the trajectory initially exhibits volatility. After a sharp initial spike—driven by brief periods of high demand and temporary market adjustments—the rent drops considerably before gradually resuming a steadier upward path, ultimately reaching around R3,400. This final increase of about 24% over the entire simulation period remains significant. This moderation primarily results from the enforced reservation of affordable units, which tempers the overall growth in rents by continuously injecting affordable housing options into the local market.

Ward 79 (Mitchell's Plain) begins with relatively lower rents, starting around R1,800, and similarly experiences considerable early volatility characterised by rapid rent increases and subsequent steep declines. After approximately the first two years, the rent fluctuations settle into a steady pattern of incremental growth, ultimately stabilizing around R1,700–R1,800. Notably, by the end of the simulation, average rents in Ward 79 essentially return to initial levels or show only minimal net growth, reflecting an effective mitigation of affordability pressures through the targeted policy mechanisms. In Ward 79, the explicit reservation of affordable units, coupled with substantial rent discounts, effectively caps the escalation of rents, protecting residents against severe affordability crises and significantly limiting displacement pressures that would otherwise emerge from NbS-driven increases in neighbourhood desirability.

6.1.3 Scenario 2: Targeted Rent Subsidy

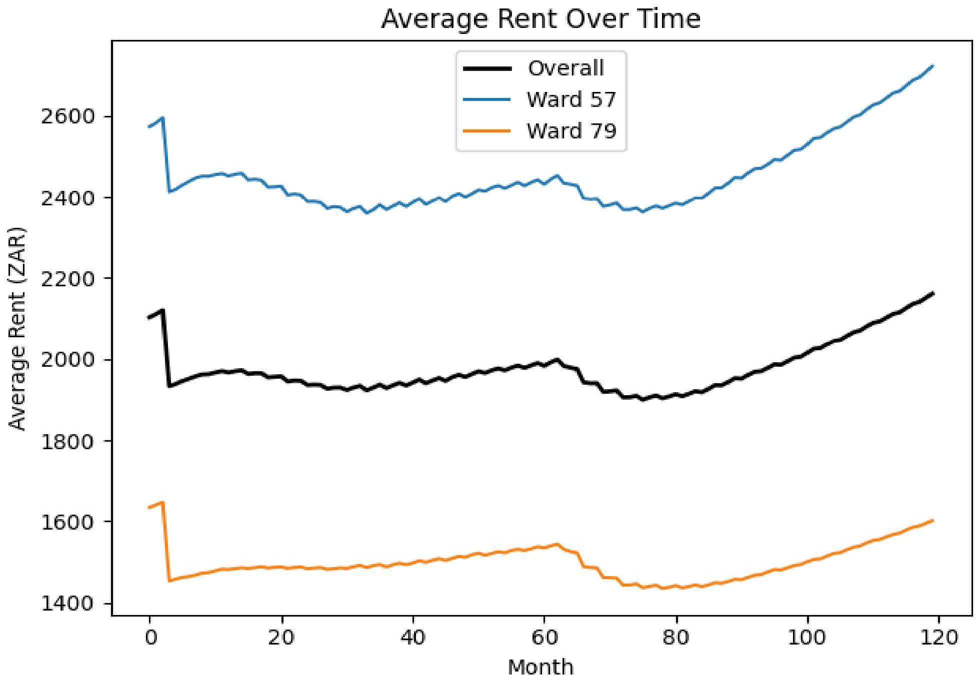


Figure 7: Avg Rent over Time for Scenario 2

This scenario aligns with Cape Town's broader housing objectives of maintaining affordability through subsidised rental schemes, particularly focusing on households near newly implemented green amenities. In practice, households located within an 800-meter radius of newly installed NbS sites receive a 20% temporary rent subsidy for five years (60 simulation steps), along with a 15% reduction in eviction risk for households directly benefiting from NbS.

Citywide, Scenario 2 displays a notably tempered rent trajectory compared to previous scenarios, with initial average rents around R2,200 increasing only moderately, ultimately settling at approximately R2,150 by the end of the ten-year simulation period. Interestingly, the citywide rent trend includes a distinctive period of slight decline and stabilization in the first few simulation years. This pattern—evident through multiple subtle kinks and plateaus—is attributed to the immediate application of targeted subsidies as NbS sites become active. As patches are progressively upgraded, qualifying households near these sites suddenly benefit from discounted rents, causing a temporary suppression or even slight decline in the overall average rents paid, thus creating the visible initial dip and plateau effect in the graph.

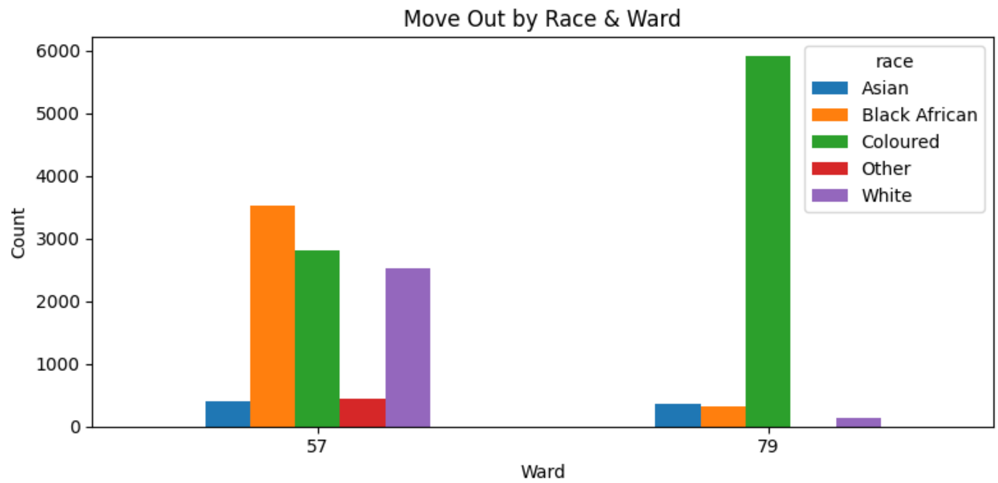
The impact of this targeted subsidy approach is particularly pronounced in Ward 57, initially starting with rents around R2,600. In the first years following the implementation of the subsidy, the graph shows a clearly rugged pattern—marked by short-term fluctuations characterised by sharp decreases followed by incremental recoveries. Over time, after approximately 60 simulation steps (five years), as the initial subsidy periods expire, rents begin to steadily increase again, surpassing the starting point and eventually reaching around R2,750 by the end of the simulation. This gradual yet eventual rebound underscores the temporary nature of the subsidy: while initially effective at curbing sharp rent increases, the subsidies' expiration allows rents to resume a trajectory driven by persistent market pressures, inflation, and rising neighbourhood desirability due to NbS interventions.

A similar pattern emerges in Ward 79 (Mitchell's Plain), initially characterised by lower rents around R1,600. These fluctuations again arise directly from the intermittent activation of rent subsidies in response to new NbS installations, which briefly stabilize or decrease the neighbourhood's average rents each time. The subsidies thus effectively buffer residents from rapid initial displacement pressures caused by the market-driven rent increases that typically accompany neighbourhood improvements. While this intervention allows residents to stay in their homes for longer instead of facing abrupt eviction, it also only delays the eventual eviction of low-income households.

6.2 Residential Displacement Patterns by Income and Race

A central concern of the simulation is to identify precisely who gets displaced by rising housing costs, and who subsequently replaces them. The model tracked residential moves both into and out of specific wards, facilitating detailed analyses of displacement through racial and income perspectives. These mobility dynamics are presented in Figure 8 (Move-Outs and Move-Ins by Race and Ward, respectively), as well as corresponding figures depicting the income distributions of movers.

6.2.1 Baseline Scenario



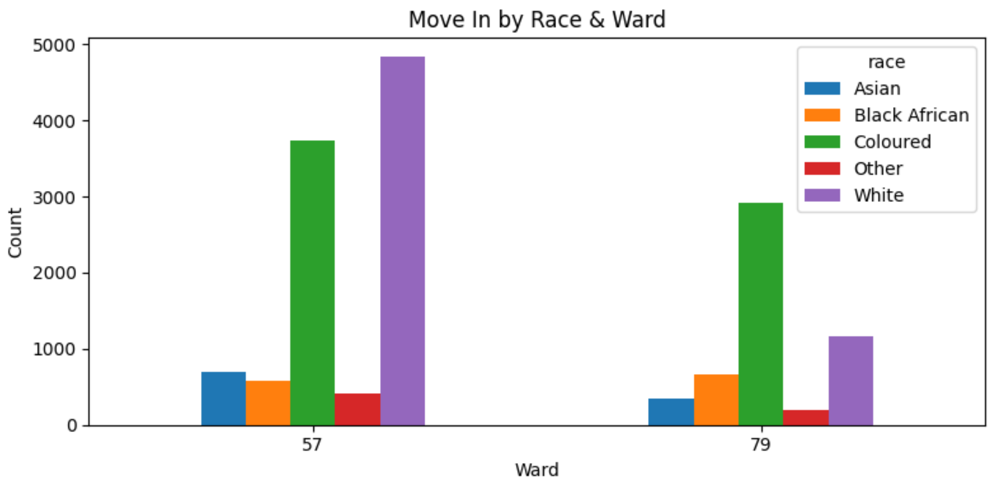
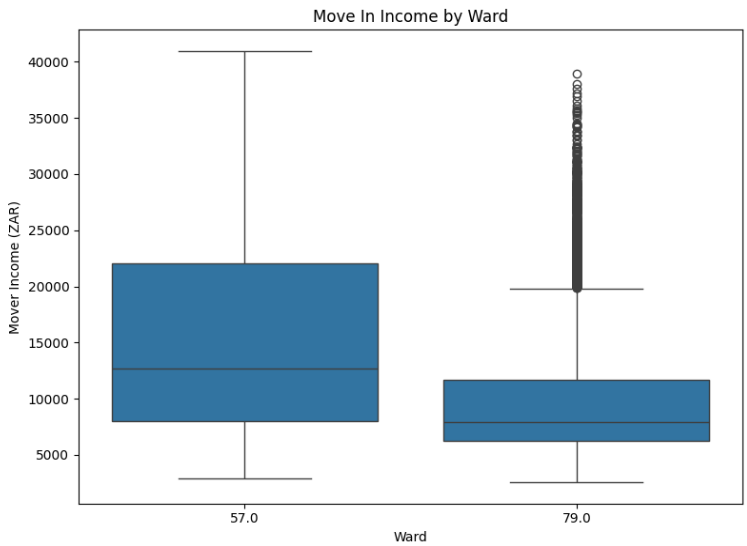


Figure 8: Migration Graphs – Basecase Scenario

Under baseline conditions, characterised by an absence of policy protections, displacement rates were notably high, disproportionately affecting lower-income and historically marginalised racial groups. Specifically, Ward 79, saw significant displacement of its original majority population—primarily Coloured households (around 6,000 households). In contrast, the outflow of other racial groups, particularly White households, was minimal due to their initial near-absence in this ward. The disproportionate impact underscores the vulnerability of the Coloured community to rent escalations associated with neighbourhood improvements.

As illustrated in the graphs, thousands of Black African households (approximately 3,500) and Coloured households (approximately 3,000) relocated from ward 57 during the simulation period, highlighting that displacement in Ward 57 was not restricted to a single racial group but was widespread among historically marginalised populations. Interestingly, a substantial number of White households (around 2,500) also left Ward 57.



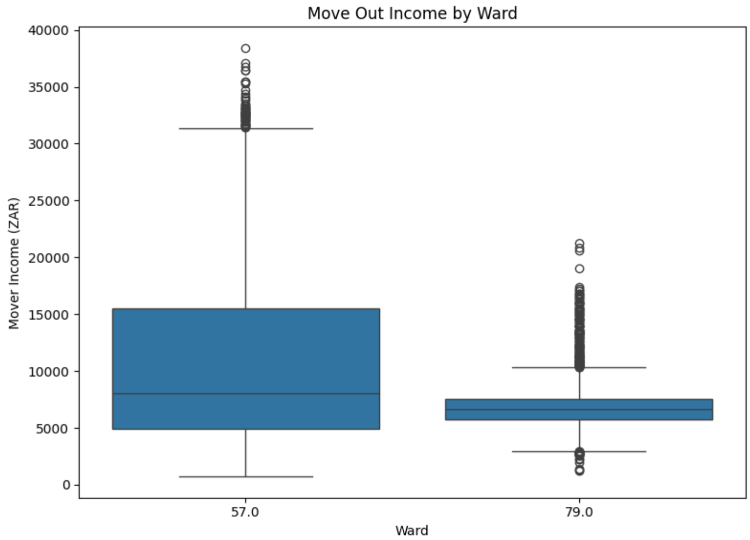


Figure 9: Income Graphs – Basecase Scenario

Income data further corroborate the displacement patterns identified through racial analysis. Figure 9 (Move-Out Income by Ward) indicates that households leaving Ward 79 generally earned lower incomes, with median monthly incomes ranging roughly between R5,000 and R6,000, coupled with a significant cluster of very low-income outliers.

On the inverse side, identifying who replaced these departing residents provides critical insights into the gentrification process triggered by NbS-driven neighbourhood improvements. As represented in Figure 9 (Move-Ins by Race and Ward), Ward 79 experienced an influx of White residents, despite their initially negligible representation. Approximately 1,200 new White households moved into the area, considerably increasing their demographic share. Additionally, a modest but meaningful number of Black African households entered Ward 79, increasing their share from 5% to 21%. Meanwhile, Coloured household move-ins (~3,000 households) fell short of replacing the significant outflow (~6,000 households), clearly illustrating a shift toward a racially different and economically more advantaged demographic.

In Ward 57, the incoming demographic shift presents an intriguing pattern: the largest group of movers into the ward were Coloured households (approximately 3,800 households), significantly outnumbering their move-outs. Conversely, White and Black African households' move-ins were fewer, resulting in a declining share of White residents within Ward 57 from approximately 27% to about 17%. This demographic shift points toward Ward 57 serving as a comparatively more affordable relocation area for households displaced from higher-pressure neighbourhoods, balancing a degree of diversity yet also reflecting clear racial dynamics.

In sum, the baseline scenario vividly illustrates the classic displacement dynamic associated with urban greening interventions. Lower-income, predominantly Coloured families were disproportionately displaced from their original neighbourhoods (particularly Ward 79), replaced largely by higher-income and racially different groups attracted to the improved conditions facilitated by Nature-based Solutions. Simultaneously, Ward 57 experienced shifts toward higher median incomes and altered demographic compositions.

6.2.2 Scenario 1: Inclusionary Housing

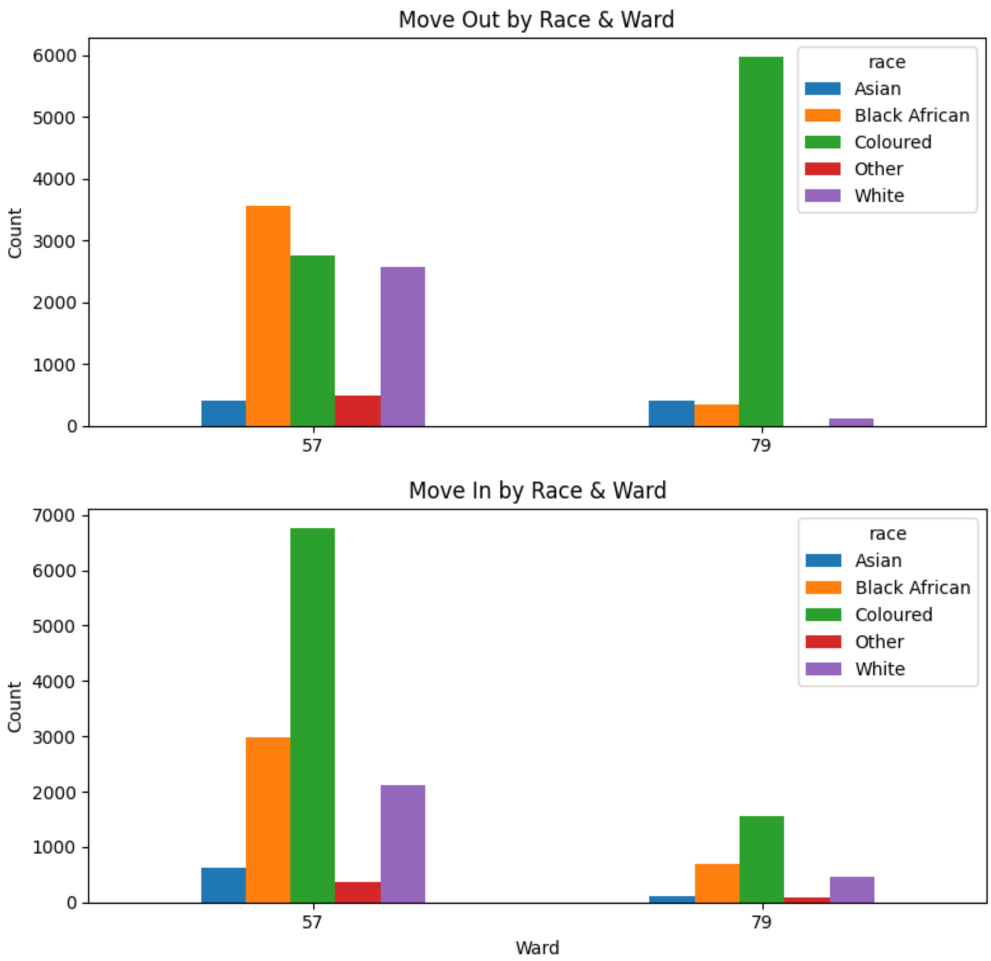


Figure 10: Migration Graphs – Scenario 1

Ward 57 shifts from being a net sender in the baseline run to a strong receiver of new residents. Roughly 6,800 Coloured households and 3,000 Black African households move into the ward, compared to the 2,800 Coloured and 3,500 Black African households that leave. The reversal of flow is a direct artefact of the reserved-unit rule: once a market-rate dwelling falls vacant, there is a 50 percent chance it will be offered at a reduced rent to a qualifying low-income applicant. Those subsidised offers draw in large numbers of historically excluded groups who would previously have been priced out of Observatory. In parallel, the move-out stream from Ward 57 retains a mixed character—still containing sizeable numbers of Coloured, Black African, and White households, but its composition subtly shifts upward along the income scale. The box-and-whisker plot of move-out incomes reveals a median just above R 8,000 per month and a fairly long upper tail, suggesting that many of the households who exit are middle-income tenants.

In Ward 79, even with the inclusionary rule in force, the ward still loses a large share of its original Coloured population, about 6 000 households, yet that outflow is no longer matched by a sizeable inflow of wealthier, racially distinct groups. Only 400–500 White households arrived over the decade

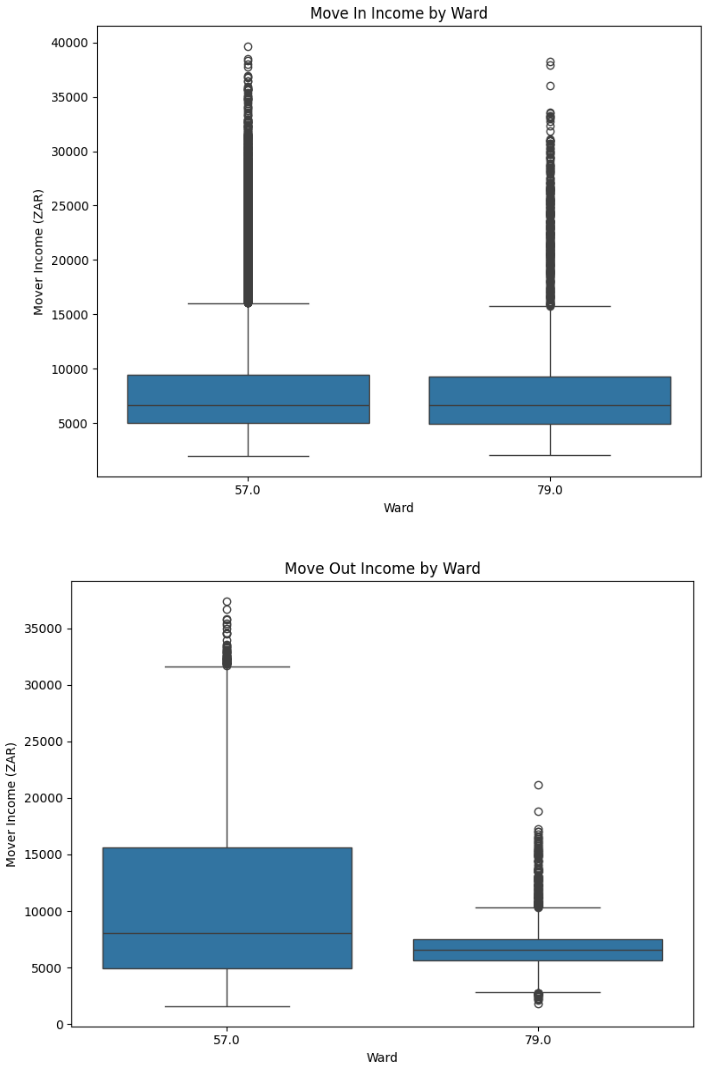


Figure 11: Income Graphs – Scenario 1

(compared with more than a thousand under the baseline run) and the Coloured inflow amounts to just 1,500 households, leaving a net deficit but a far shallower one than before. The reform therefore dulls, though does not fully eliminate, the green-gentrification pressure that had previously transformed the ward's demographic make-up.

Taken together, these patterns confirm the central intuition behind Scenario 1. By coupling Nature-based Solution roll-outs with binding inclusionary quotas, the city succeeds in anchoring low-income households within high-amenity areas (hence the dramatic inflow of Coloured and Black African households to Observatory) and in dampening the replacement of low-income communities by high-income entrants in Mitchell's Plain. Displacement pressures are not eradicated. Ward 79 still records a sizable out-migration of Coloured households but their intensity and their redistributive consequences are significantly moderated.

6.2.3 Scenario 2: Targeted Rent Subsidy

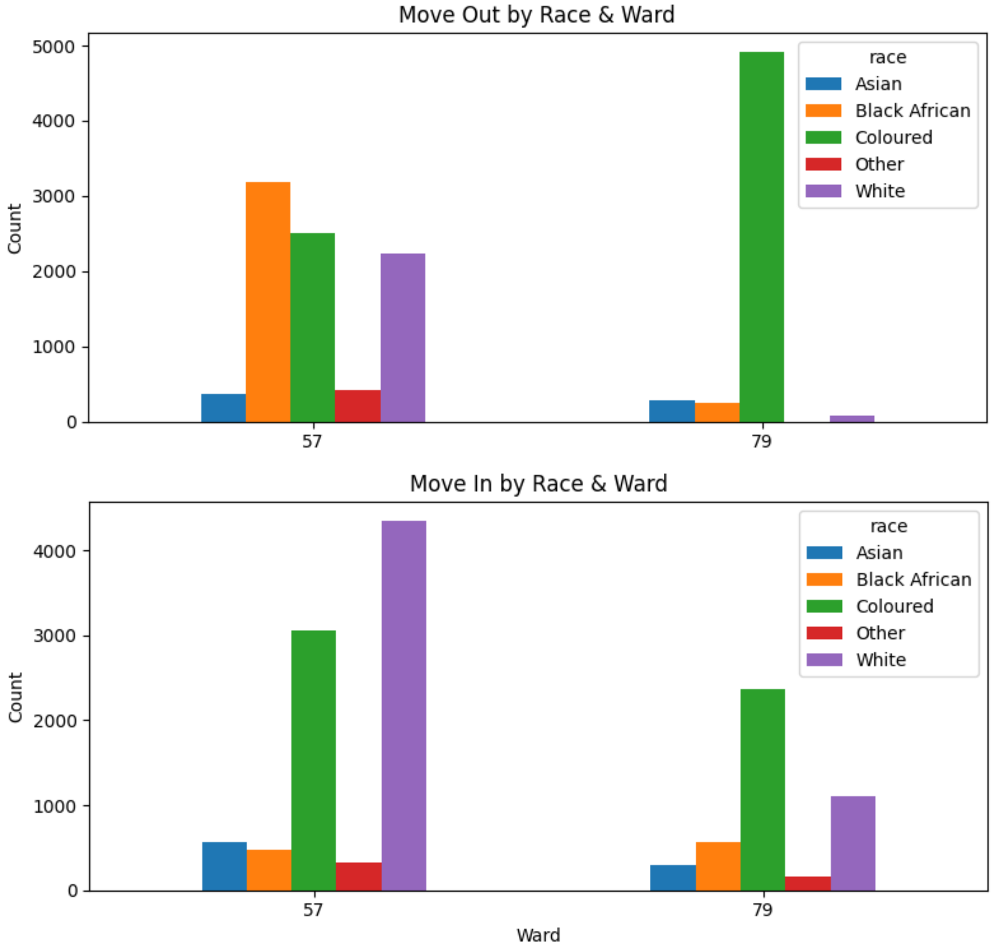


Figure 12: Migration Graphs – Scenario 2

Under the targeted rent-subsidy scenario, in which households living within eight hundred metres of a Nature-based Solution receive a discount for five years and enjoy a modestly lower probability of eviction, the demographic story is one of delayed, though ultimately incomplete, displacement.

In Ward 79, the subsidy cushions the original community during the first half of the simulation. By the end of the ten-year run roughly 4,800 Coloured households have left, a large number but significantly fewer than under the unregulated baseline. Out-migration among other groups remains modest: only a few hundred Black African and Asian households depart, and White households' departures are negligible. The inflow picture, however, shows that gentrification pressures are merely postponed rather than removed. About 2,400 Coloured households arrive, joined by approximately 1,100 White households. Median mover incomes make the same point in economic terms: newcomers earn around R 8,000 to R 9,000 per month, while those who leave average closer to R 6,000–7,000. The subsidy narrows, but does not fully close, the income gap that drives long-term affordability concerns.

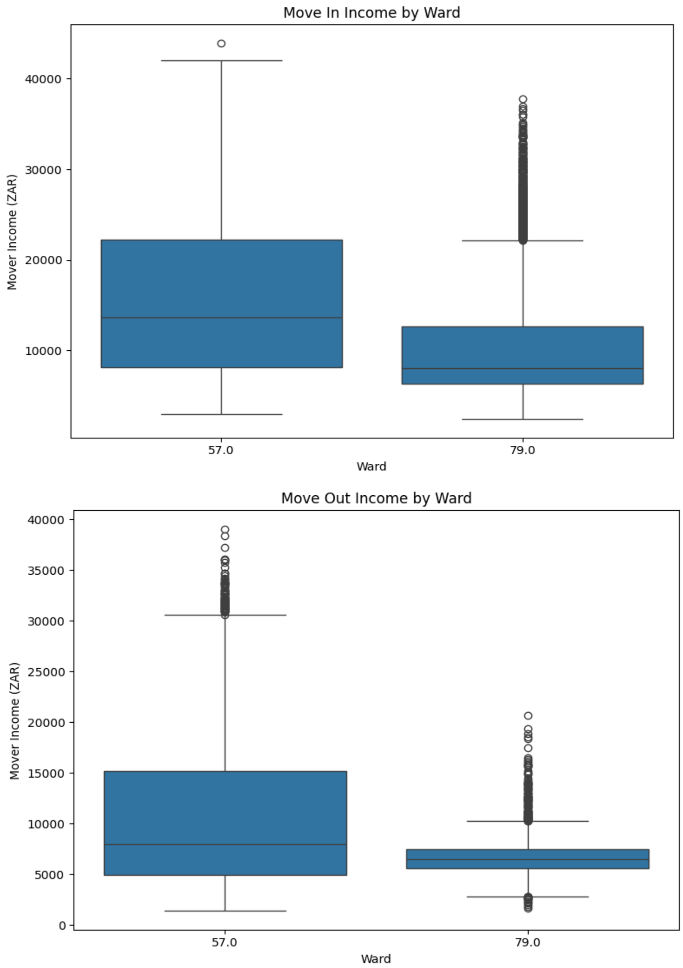


Figure 13: Income Graphs – Scenario 2

Viewed together, these patterns confirm that the subsidy does what it was designed to do: it buys vulnerable households time by dampening rent shocks and reducing immediate eviction risk. During the five-year discount window, displacement slows markedly, and the dramatic early exodus seen in the baseline run never materialises. Yet because the protection is temporary and tied to incumbent leases rather than to the housing stock itself, the underlying market momentum only pauses. Once discounts expire, rents continue their upward march, vacancies reopen, and higher-income entrants begin to arrive. The result is a gentler, slower gentrification trajectory: the ward grows whiter and wealthier, though less abruptly than under laissez-faire conditions.

6.3 Demographic Shifts: Changes in Racial Composition

This section explores the racial demographic changes observed across the three modeled scenarios, drawing explicit links to the patterns of residential displacement detailed in the previous section. The results demonstrate how NbS, when introduced without accompanying safeguards, can catalyse significant changes in neighbourhood composition through rent-based displacement, while equity-focused policy designs can substantially mitigate these shifts. The patterns of demographic change reinforce and extend the trends already discussed in relation to overall household movement and affordability thresholds, adding a crucial racial lens to the model's distributional outcomes.

Importantly, these patterns of racial displacement are a structural consequence of Cape Town's inherent correlation between race and income. As long as low-income households—disproportionately Black African and Coloured—remain most vulnerable to rising housing costs, any gentrification driver that elevates rent pressure is likely to reproduce these racialised outcomes. The NbS-led displacement dynamics observed here should therefore be understood as one manifestation of this deeper socio-economic inequality, rather than a unique byproduct of green interventions. Different forms of urban redevelopment would likely produce similar demographic effects unless these underlying disparities are addressed.

6.3.1 Baseline Scenario

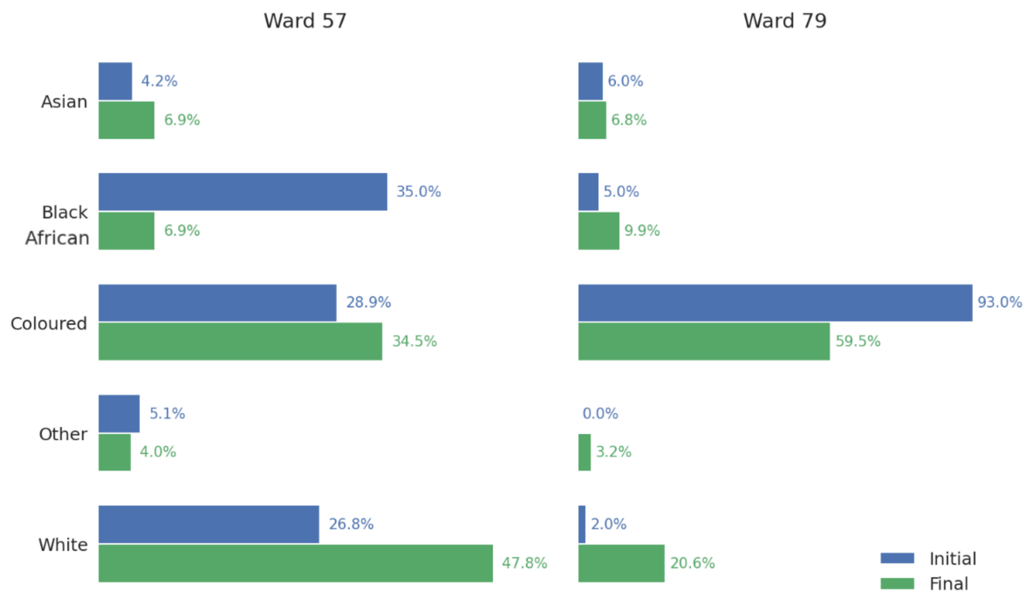


Figure 14: Demographic Shifts- Baseline Scenario

In the baseline model, which assumed no new NbS interventions or anti-displacement mechanisms, racial shifts unfolded as a consequence of unregulated market forces operating in historically unequal neighbourhoods. Ward 57 saw a notable increase in the proportion of White residents, rising from 26.8% to 47.8% by the final simulation step. This growth occurred alongside a sharp decline in Black African households, who dropped from 35.0% to just 6.9%. These changes are consistent with the earlier findings on rent dynamics: the desirability of Ward 57 made it a target for high-income in-movers, pushing rents beyond the affordability threshold of many existing households. Coloured households in Ward 57 experienced a moderate increase, suggesting that they may represent a transitional demographic group capable of withstanding some rent increases but still vulnerable to eventual pricing out.

In contrast, Ward 79, initially dominated by Coloured households at 93%, experienced partial demographic inversion. The Coloured population fell to 59.5%, while White residents increased from a negligible 2.0% to 20.6%, and Black African households rose from 5.0% to 9.9%. This result is particularly telling: even in a lower-income ward not explicitly targeted for greening or renewal, market effects spilled over, perhaps due to its relative affordability compared to increasingly unaffordable neighboring areas. The increase in higher-income, non-local in-movers thus displaced Coloured households in Ward 79 despite its initial demographic. This scenario illustrates how structural inequality, compounded by unregulated rent inflation, can replicate green gentrification dynamics even in the absence of formal NbS introduction.

6.3.2 Scenario 1

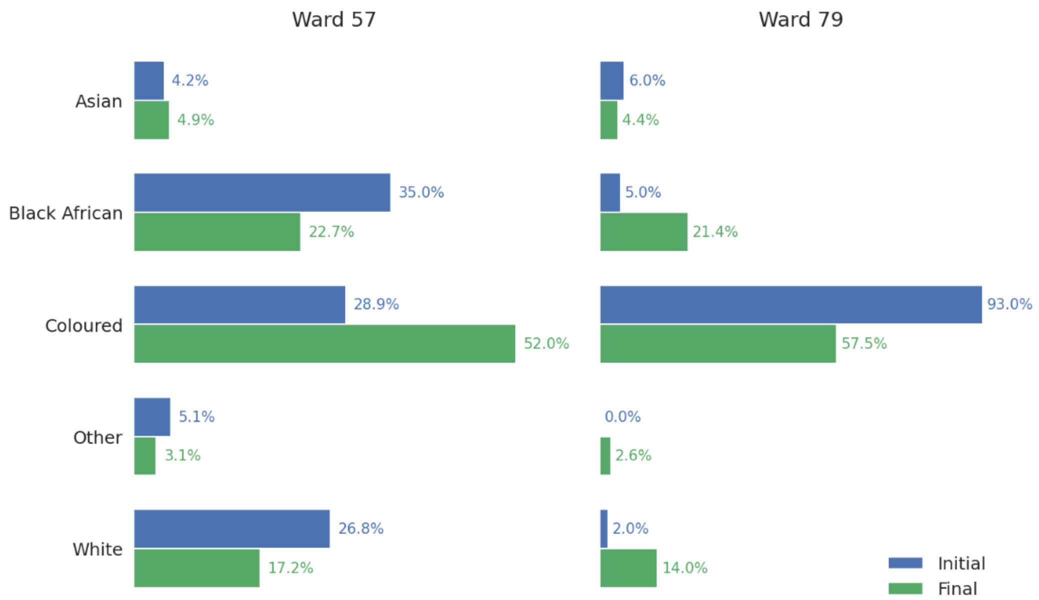


Figure 15: Demographic Shifts- Scenario 1

This intervention produces a demographic profile in Ward 57 that differs markedly from the baseline. Rather than accelerating White in-migration, the share of White residents surprisingly decreases to 17.2%. In contrast, Coloured households increase dramatically to 52.0%, and Black African households make up 22.7%. This suggests that rent stabilization for vulnerable households—combined with reserved access—disrupted the typical gentrification trajectory and allowed for greater demographic retention and even moderate in-migration of mid-income Coloured and Black African households. The presence of NbS may have still increased desirability, but the demographic shifts point to controlled integration rather than exclusion.

In Ward 79, the results echo this protective logic. Coloured residents remain a dominant group at 57.5%, while Black African and White households increase to 21.4% and 14.0% respectively. Rather than displacement, the racial profile becomes more balanced without sharply displacing incumbent communities. In short, inclusionary housing preserves socio-economic diversity by ensuring that NbS improvements are not monopolized by higher-income entrants. These results underscore the critical importance of embedding equity considerations directly within urban planning mechanisms.

6.3.3 Scenario 2

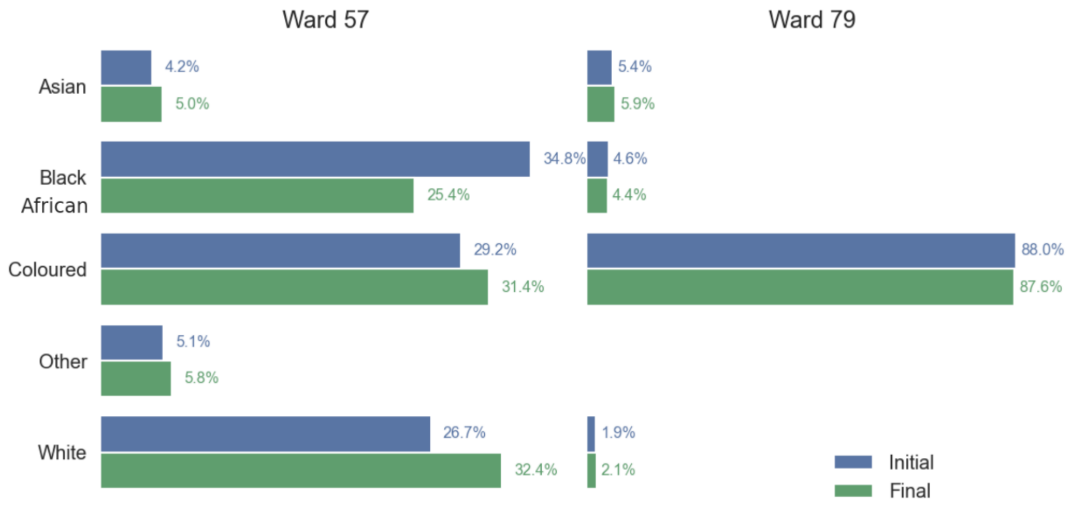


Figure 16: Demographic Shifts- Scenario 2

In Ward 57, the share of White households rises modestly to 32.4%, with Black African and Coloured populations stabilising at 25.4% and 31.4%, respectively. This balanced outcome reflects both the attractiveness of the upgraded environment and the protection afforded by targeted subsidies. Unlike the baseline, upward migration into the area does not lead to disproportionate exclusion.

Ward 79 similarly maintains a stable demographic profile. Coloured residents remain overwhelmingly dominant at 87.6%, a marginal decline from the initial 88.0%. The minor increases in White and Black African populations reflect growing interest in the area but are not suggestive of mass displacement. This relative stasis, achieved through time-bound relief measures, affirms that even temporary interventions can substantially delay or soften the intensity of market-driven demographic shifts.

Taken together, the findings across both scenarios reveal that well-calibrated and spatially sensitive policy tools—whether through mandated affordability or targeted subsidies—can materially alter the demographic consequences of urban greening. These patterns reinforce the core argument established in the displacement section: that rent-based thresholds are crucial predictors of vulnerability, and interventions must be designed to address them head-on. Demographic shifts, when interpreted through this lens, serve not just as population statistics but as indicators of spatial justice and the moral quality of urban transformation.

6.4 Livability Outcomes

A key objective of the modeled nature-based interventions was to improve urban livability through enhancements in environmental quality, aesthetics, and local amenities. This was quantified using a Livability Score, a composite index of green cover, heat and pollution. Figure B (Liveability Score Over Time) shows the evolution of this score over the simulation period, with results reported for the city overall and for Wards 57 and 79.

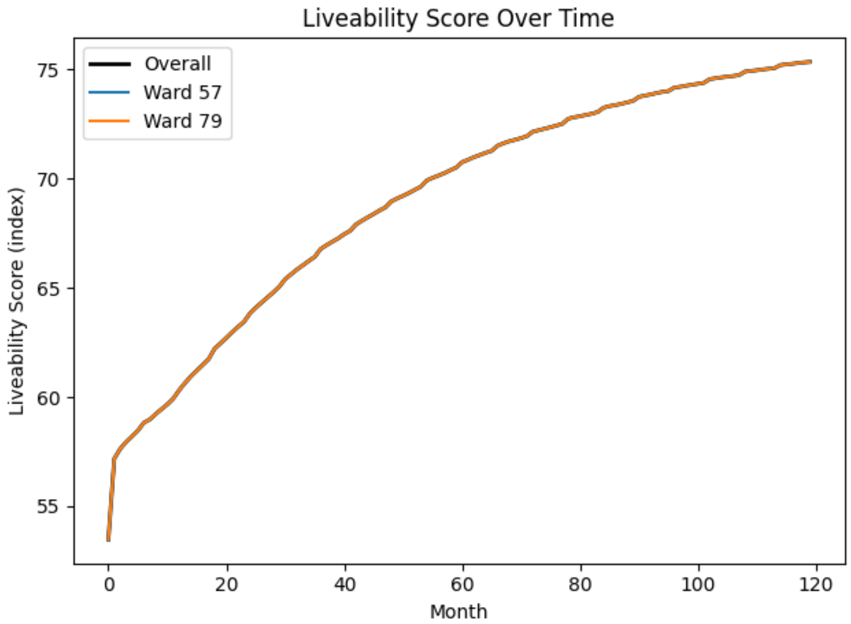


Figure 17: Livabality graph

Across all scenarios, livability follows a consistent and strongly upward trend, rising from an initial value of about 54 to approximately 75 by year ten. This trend reflects the cumulative success of NbS in enhancing neighbourhood quality of life. Importantly, since the physical infrastructure improvements remain constant across all scenarios, the Livability Score exhibits the same trajectory regardless of housing policy context. The visual convergence of the lines for Ward 57, Ward 79, and the overall city indicates that gains in livability were distributed relatively evenly in spatial terms.

However, the livability metric does not tell who actually benefits from these improvements. In the baseline scenario, many original residents of Ward 79 were displaced by year ten, meaning that the elevated livability score at the end of the simulation reflects the experiences of newer, wealthier residents rather than the historical community. This underscores a central paradox: while NbS increased livability, the displacement of vulnerable groups meant that those most in need of environmental improvements were not the ones who ultimately enjoyed them.

Inclusionary Housing (Scenario 1) corrects this misalignment. By guaranteeing that low-income residents remain in place, the policy ensures that the beneficiaries of livability improvements are those who endured prior environmental degradation. This reinforces the idea of equitable greening: it is not enough to raise livability metrics; it matters who gets to live in the improved environment. Scenario 2 (Targeted Rent Subsidies) delivers a partial solution. Residents benefit during the subsidy period and remain in place to experience at least some of the livability rise. However, once the subsidy ends, some displacement resumes, meaning that final-year livability scores again represent a mix of original and newer residents.

The minor zig-zag patterns in the graph reflect month-to-month housing transitions, such as tenant movement or temporary evictions, which influence patch-level scores. These fluctuations are an emergent property of agent-based dynamics. They signal the micro-dynamism of urban change: even when the broader trajectory is positive, communities experience these improvements unevenly and episodically.

Overall, this chapter highlights that livability gains alone cannot be used as a metric for success. Their distribution—and the preservation of community identity and residence—are equally critical. As such, achieving a just green transition in Cape Town requires not only environmental innovation but deliberate socio-political safeguards to ensure that those most in need are not left behind.

6.5 Tracking Change Across Wards

This section discusses the spatial effects of the NbS on the wards, particularly regarding displacement.

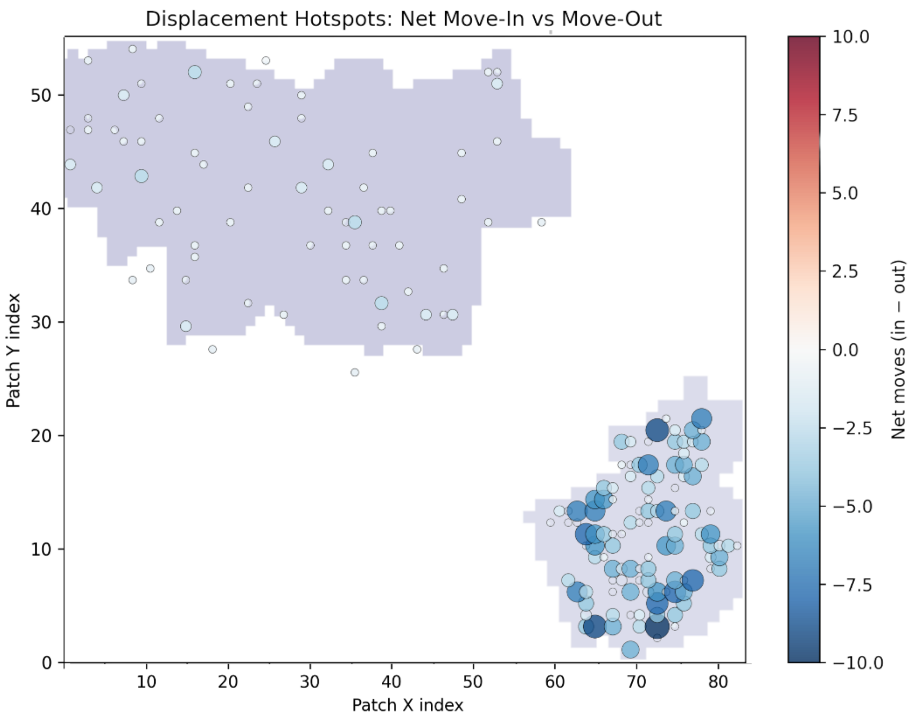


Figure 18: Displacement Hotspots

Both move-in and move-out activities are most intense in Ward 79, indicating extreme turnover in this low-income neighbourhood. Patches in Ward 79 register the highest counts of incoming households, as well as the highest counts of departures, reflecting acute displacement pressure on its already vulnerable residents. By contrast, Ward 57 exhibits relatively modest inflows and outflows, consistent with its stronger economic resilience and housing affordability. When netting these flows (in – out), Ward 79 still records substantial net losses, while Ward 57 remains near balance. Importantly, although targeted policy scenarios (e.g. rent subsidies or inclusionary zoning) reduce overall mobility, they do not alter this geographic pattern: Mitchell's Plain (Ward 79) continues to experience far more churn and net out-migration than Observatory (Ward 57). This highlights the need for context-specific policy interventions which are tailored to help the specific people they will be affecting.

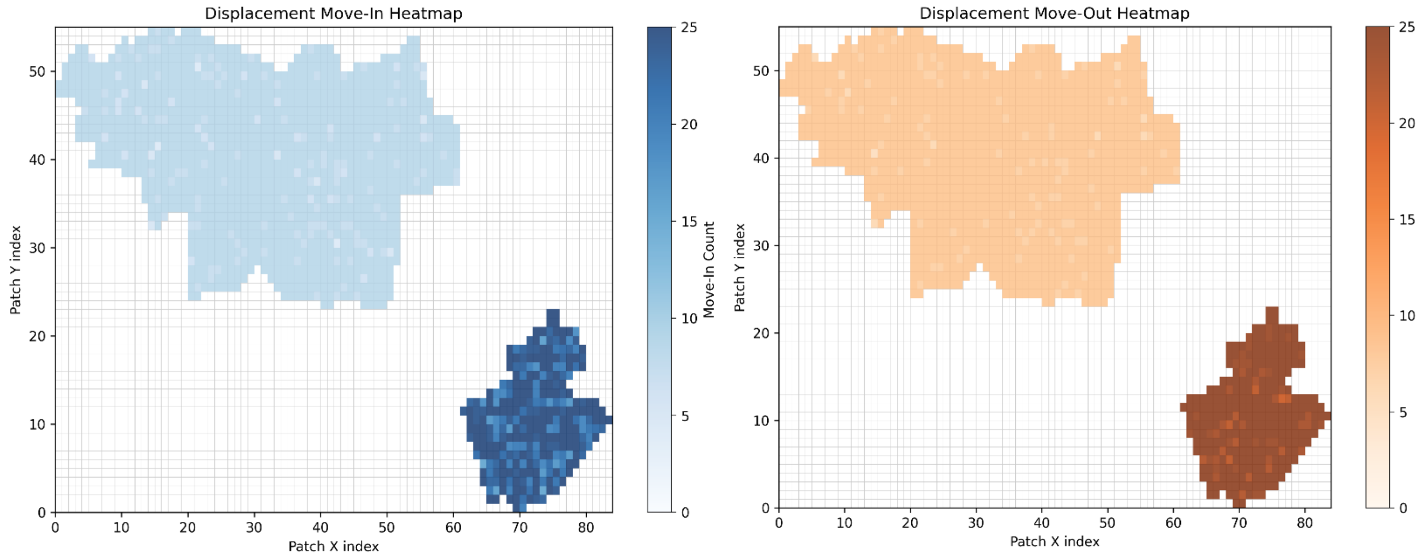


Figure 19: Displacement Hotspots (move in & move out)

6.6 Sensitivity Analyses

To evaluate the robustness of the displacement outcomes to rent-burden pressures, the agent-based model was executed in repeated simulations with systematically varied eviction thresholds (defined as the ratio of rent to household income). Each experiment was initialised with a distinct, recorded random seed (42, 123, 555, 789, 999) to ensure both reproducibility and coverage of stochastic variability in household relocation dynamics. Across these runs, the eviction threshold was incrementally increased—ranging from a 10 percent rent-to-income burden up to a 55 percent burden—while all other model parameters remained constant.

This sensitivity analysis thus isolates the effect of housing cost pressure on household displacement: by observing the percentage of original households exiting each ward as the threshold rises, it identifies the critical "inflection" points at which different racial groups become rent burdened and begin to move out in significant numbers. The ensuing section presents these results for Ward 57 (Observatory) and Ward 79 (Mitchell's Plain) under the baseline and two policy scenarios, revealing the rent-to-income levels at which vulnerability to eviction is most acute for each community.

6.6.1 Baseline Scenario

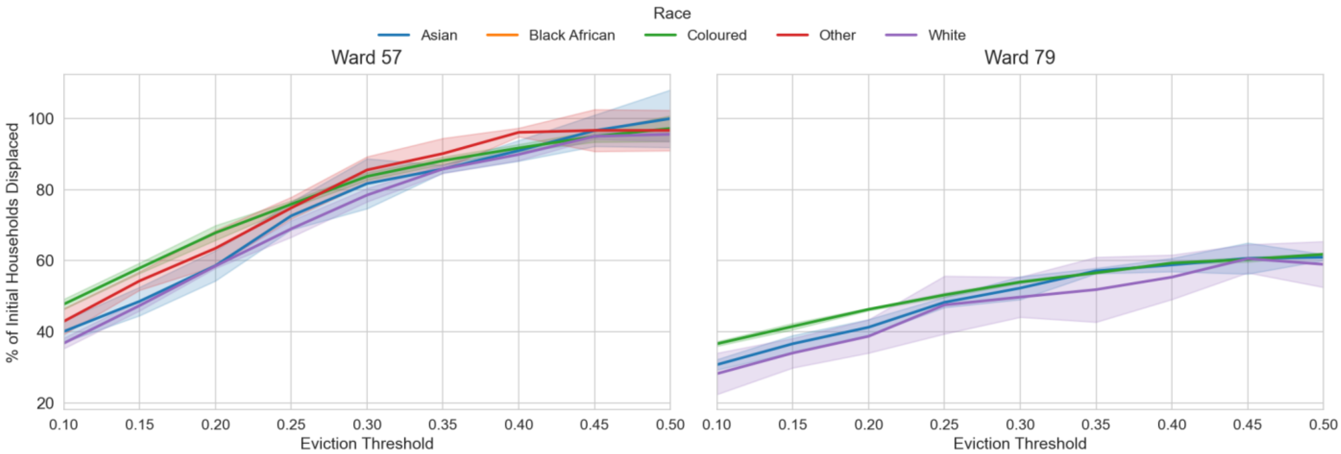


Figure 20: Sensitivity of displacement to the eviction (rent/income) threshold

Under the baseline scenario, for Ward 57, displacement occurs at very low eviction thresholds for Black African households. For example, at a rent/income threshold around 0.10 the plot indicates nearly 80% of Black African households are displaced, whereas only about 40% of White households are displaced at this point. Coloured and Other households lie in between. Each group's displacement curve is steep and concave upward: by threshold ~0.25–0.30 the slopes begin to level, and by ~0.40–0.45 almost all households of every race are displaced (all curves converge near 100% displaced). White households enjoy the greatest resilience (requiring much higher rent burdens before displacement), whereas Black African households are the most vulnerable. The confidence bands are relatively tight, underscoring the robustness of these gaps.

Displacement in Ward 79 is much milder and more gradual than in Ward 57. At an eviction threshold of 0.10, only about 30–35% of any group is displaced, which is far lower than the levels seen in Ward 57. Displacement for all groups rises slowly with threshold: by 0.20 roughly 45% of Black African and Coloured households are displaced, and by 0.30 only about 50–55% of any group is displaced. Even at the highest threshold (~0.50), the plots show that only around 60% of Black African households and a slightly lower fraction of others (White ~55%, Coloured ~60%) are displaced. Each group's line is gentle and nearly parallel to the others, indicating no early inflection until very high thresholds. Thus the onset of displacement is delayed (substantial eviction does not occur until thresholds exceed ~0.2–0.3) and the slope is gentle.

6.6.2 Scenario 1

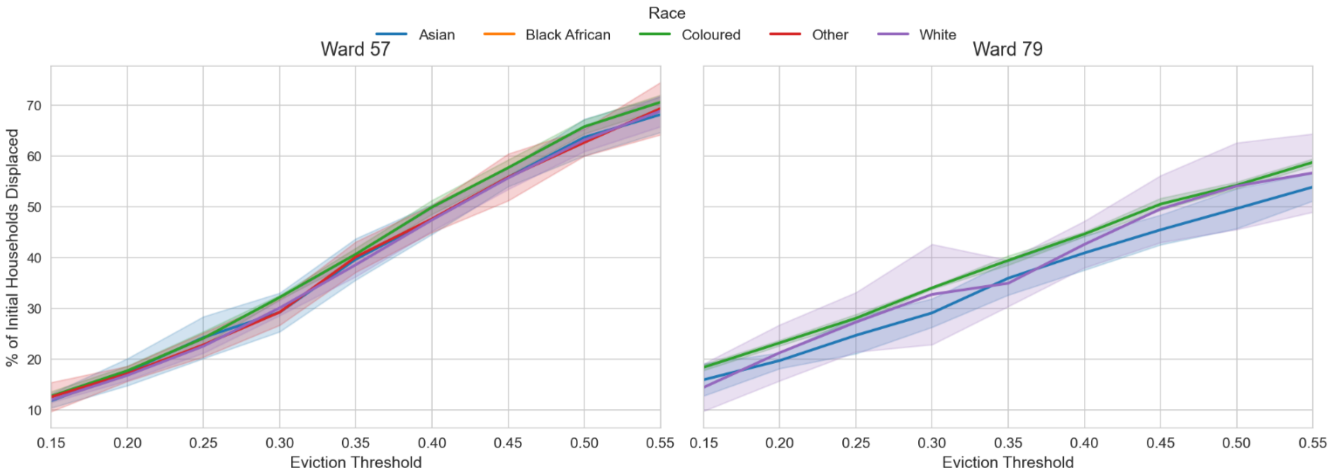


Figure 21: Sensitivity of displacement to the eviction (rent/income) threshold Scenario 1

In scenario 1, the displacement curve for ward 57, for all racial groups remains relatively low at strict affordability thresholds, then *steepen* at higher thresholds. Black African and Coloured households show the earliest sharp increases: their displacement rates start climbing steeply around an eviction threshold of roughly 0.25–0.30. Ward 57's historically marginalised groups (Black African, Coloured, Asian, Other) are *most sensitive* to loosening rent/income thresholds, whereas White households are least sensitive. Notably, these inflection orders mirror incomes: White residents can tolerate higher rent burdens, so their sharp displacement comes only at high thresholds.

In Ward 79, displacement is far more sensitive for the majority Coloured and Black African populations. When the eviction threshold passes roughly 25–30% of income, the percent of Coloured and Black African households displaced surges. The "Other" group (red) follows a similar pattern (inflection ~0.30). Asian and White curves remain flat (near 0%) until about ~0.35–0.40, then rise modestly. In particular, White households – a small minority in Ward 79 – experience almost no displacement until the threshold is very high (~0.40), reflecting both their low initial numbers and relatively higher incomes.

Racial Group	Ward 57 Inflection Threshold (approx.)	Ward 79 Inflection Threshold (approx.)	Relative Sensitivity
Coloured	~0.25–0.30	~0.25–0.30	High in both wards
Black African households	~0.30	~0.25–0.30	High in both wards
Asian	~0.30	~0.30–0.35	Moderate
Other	~0.35	~0.30	Moderate
White	~0.40	~0.40	Low sensitivity

Table 2: Comparative Inflection Thresholds by Race

Approximate "inflection" thresholds are where each curve's slope rises sharply (from Fig.19). The confidence bands (shading) indicate uncertainty: for example, the Black African households households and Coloured curves have relatively narrow CI around their steep sections, confirming robust threshold points, whereas the White curves show very low displacement (and narrow CI) until ~0.40.

6.6.3 Scenario 2

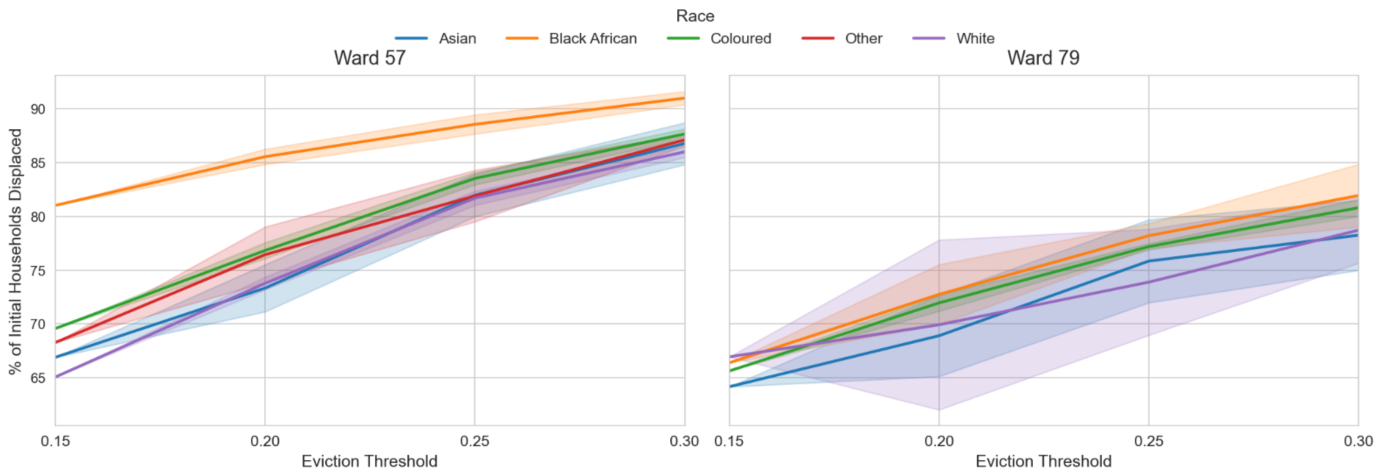


Figure 22: Sensitivity of displacement to the eviction (rent/income) threshold Scenario 2

Similar to the previous results, the historically marginalis ed groups are *most sensitive* to loosening rent/income thresholds, whereas White households are least sensitive. Across both wards and scenarios, the historically marginalised groups are most vulnerable: Coloured and Black African households hit the inflection at the lowest thresholds, meaning even moderate rent/income stress triggers mass displacement. By contrast, White households are comparatively insulated. This racialized pattern aligns with the wards' socio-spatial context.

Chapter 7: Discussion

7.1 Simulation Outcomes

7.1.1 Rent Trends

The simulations reveal that nature-based solutions (NbS), when implemented without accompanying housing policy, exert substantial upward pressure on rents across the urban system. In the Baseline scenario, average rents escalate, driven by increased amenity value and heightened competition for housing near newly greened areas. This effect is most pronounced in Ward 57, where rents climb from approximately R2,600 to R3,250 over the decade, illustrating a steep ≈25% increase. Conversely, Ward 79, a lower-income area, experienced a milder rent rise, with rents increasing from around R1,600 to R1,800, reflecting both its starting position and relatively lower demand pressures.

By contrast, Scenario 1 (Inclusionary Housing) demonstrates a marked dampening effect on rental inflation. Citywide rents increase by a more modest ≈18% by year 10, stabilizing around R2,600. In Ward 57, the upper-bound trajectory is moderate, with average rents reaching ~R3,400, a significant slowdown compared to Baseline. Ward 79 fares even better, with rents held effectively flat over the simulation due to the continuous injection of capped and discounted units reserved for lower-income households. The inclusionary zoning mechanism acts as a structural counterbalance to market escalation.

Scenario 2 (Targeted Rent Subsidy) similarly restrains rent increases, but through a time-limited intervention. The rent trajectory across the city dips initially due to subsidy injections and remains relatively stable until the five-year mark, when the subsidy expires. Thereafter, rent levels begin to climb again, particularly in high-demand areas. While the targeted subsidy approach buys time and reduces short-term affordability stress, it does not permanently alter the market structure. Only Scenario 1 generates enduring affordability due to its embedded, policy-driven housing allocation rules. Therefore, if targeted rent subsidies have to be implemented (as in scenario 2), they should be accompanied with some inclusionary housing policies once the subsidy period expires. Otherwise, the displacement of people is not avoided, simply delayed. However, this delay is not meaningless, it allows families and households to continue living in their neighbourhoods for longer than they would have been able if no policy was implemented. This also gives households' a buffer time period to make alternative housing arrangements, thus making the eviction less abrupt.

7.1.2 Displacement Patterns

In the absence of policy safeguards, NbS implementation produces extensive displacement of historically marginalised populations. The Baseline scenario leads to the mass out-migration of low-income residents from both Wards 79 and 57. In Ward 79, over 6,000 Coloured households are displaced, replaced by higher-income entrants—primarily White and Black African households—who contribute to a rising median income profile in the ward. This inflow results in a dramatic reshaping of the ward's demographic and economic character. Ward 57 similarly undergoes significant turnover, with 3,500 Black African and 3,000 Coloured households leaving over the decade. Notably, even 2,500 White households exit, suggesting displacement pressures affect moderate-income residents as well.

Scenario 1 fundamentally disrupts this displacement cycle. The inclusionary housing provision enables people to move into ward 57, and actually reap the benefits of the urban greening. It allows low-income migrants to move in, attracting over 6,800 Coloured and 3,000 Black African households while curbing the exodus observed in the Baseline. Ward 79 continues to see outflows, but at a moderate rate, and critically, the incoming population under Scenario 1 includes a higher proportion of Coloured and low-income households. These dynamics reflect a redistribution of opportunity rather than a wholesale replacement, indicating a more equitable trajectory.

In Scenario 2, following the expiration of the five-year subsidy period, average rents in Ward 79 slowly began to rise once again, stabilizing near approximately R1,600—indicating essentially negligible net growth in rents by the end of the simulation period. This final stabilization suggests that, particularly in lower-income areas, even temporary subsidies can provide lasting affordability benefits by reducing early displacement and slowing the cumulative rent-growth trajectory. During the five-year subsidy window, displacement is significantly reduced in ward 79—only 4,800 Coloured households leave, and very few Black African or White households are displaced. However, once the subsidies lapse, displacement accelerates again. By year 10, the ward exhibits an uptick in higher-income in-movers, and ward 57 begins to attract affluent residents, echoing Baseline patterns. This scenario therefore reflects a temporally bounded mitigation effect that eventually gives way to market-driven dynamics.

7.1.3 Demographic Restructuring

The end-state demographic compositions in each scenario highlight the cumulative impact of different policy strategies. Under Baseline conditions, Ward 79 transitions from a homogeneously Coloured community (~93%) to a more racially diverse but economically stratified ward (57.5% Coloured, 21.4% Black African, 14% White households). This transformation exemplifies a classic demographic inversion driven by gentrification. Conversely, Ward 57 shifts toward a majority-Coloured population, indicating a form of spatial redistribution of socio-demographic burden.

Scenario 1 preserves community composition to a greater extent. By year 10, Ward 57 retains majority Coloured households (52%), with balanced Black African households (23%) and White households (17%) representations. Similarly, Ward 79 retains its majority of Coloured households (57.5%), a notable achievement given the intense gentrification pressures observed in the Baseline. These outcomes are consistent with a framework of inclusive sustainability: the physical neighbourhood improves, but the social community remains intact.

Scenario 2 reflects an intermediary trajectory. Ward 79's majority of Coloured households remains relatively intact (87.6%), only slightly down from its initial level, suggesting that the subsidy postpones demographic transition. However, in Ward 57, the White households' share increases to 32.4% and Coloured households to 31.4%, reflecting a subtle but detectable shift toward racial and income diversity. Ultimately, this scenario reflects deferred rather than defused demographic restructuring.

7.1.4 Livability Outcomes

Across all scenarios, NbS produce significant improvements in livability scores. Under Baseline conditions, the citywide livability index rises from approximately 54 to 75 over ten years. This increase is mirrored in both Wards 57 and 79, suggesting a broad spatial diffusion of environmental benefits. However, the social distribution of these gains is highly uneven.

In the Baseline, livability gains accrue primarily to incoming, wealthier households, as most original low-income residents have been displaced by the time peak livability is reached. This constitutes a spatial-ecological paradox: while the environment improves, the beneficiaries are not the original inhabitants who endured previous deprivation.

Scenario 1 reverses this pattern. By embedding affordability through inclusionary quotas, the policy ensures that original low-income residents—particularly Coloured and Black African households—remain in place to enjoy the benefits of NbS. This outcome represents a critical alignment of environmental and social goals. Ward 57 similarly experiences improved livability without the burden of absorbing large numbers of displaced residents, further supporting the conclusion that inclusionary housing fosters spatial justice.

Scenario 2 offers partial redress. During the subsidy period, incumbent households benefit from the rising livability, but post-subsidy displacement undermines these gains. Although more residents remain in Ward 79 than under Baseline, the final composition still skews toward wealthier groups. As such, Scenario 2 offers a temporally constrained form of inclusion—livability is shared for a time, but not secured in perpetuity.

7.2 Policy Implications

The findings of this simulation suggest that the socio-spatial outcomes of NbS are contingent not solely on the physical implementation of green infrastructure but critically on the institutional arrangements that accompany them.

First, it is evident that pairing NbS with affordability measures is essential to prevent the unintended consequence of green gentrification. In the absence of policy constraints, green amenities act as catalysts for market pressures that disproportionately displace low-income communities. The model demonstrates that inclusionary housing mechanisms can counteract these pressures and distribute benefits more equitably.

Second, the scope and duration of intervention play a decisive role. Time-limited subsidies offer immediate relief but lack staying power. Once withdrawn, the underlying structural dynamics of displacement and gentrification resume. Inclusionary zoning, by contrast, institutionalizes affordability, embedding social equity into the very fabric of urban transformation.

Finally, the design and enforcement of policy architecture determine whether NbS produce inclusive sustainability or simply repackage inequality in greener settings. The contrast between scenarios illustrates that technocratic solutions—such as green roofs and urban gardens—are insufficient without parallel commitments to justice and redistribution. Policy tools such as rent stabilization, permanent affordability quotas, and proactive tenant protections must be viewed not as peripheral, but as central to sustainable urban planning.

In sum, the simulations offer a compelling empirical basis for the claim that just and equitable urban greening requires deliberate institutional design. NbS can be a powerful vehicle for social upliftment, but only when paired with policies that ensure long-term affordability and community continuity.

7.3 Limitations

This research is exploratory and subject to several limitations, shaped by both the researcher's positionality and the simplifying assumptions of the model.

As the author has not conducted fieldwork in Cape Town, the model draws solely on secondary data and literature. This outsider perspective may miss locally grounded insights or lived experiences. The modelling process reflects subjective design decisions made within technical and data constraints, offering a stylised abstraction rather than a comprehensive representation of urban dynamics.

Several simplifications follow from this approach. Relocation behaviour is modelled through basic utility calculations, omitting factors such as social networks, commuting distance, cultural preferences, and institutional barriers. Race is included only statistically, without representing how racialized experiences shape housing access or community belonging. Livability is reduced to a composite of environmental indicators, which may not align with residents' own valuations of place or well-being.

While many key parameters such as rent uplift after NbS, eviction thresholds, and displacement risks are informed by data and planning documents specific to Cape Town, not all were subjected to sensitivity testing. This limits the model's ability to assess how results might shift under alternative, but still plausible, assumptions.

Institutional and political processes are also held static. The model does not simulate resident feedback, collective action, or policy adaptation in response to displacement pressures. Similarly, developers, landlords, and other actors are not explicitly modelled, which limits insight into strategic behaviour or opportunistic investment patterns.

Finally, spatial granularity is limited. The model represents the city as a grid of patches that abstract over intra-ward differences and localized gentrification hotspots. This may smooth over fine-scale dynamics that occur at the level of individual blocks or neighbourhoods.

Taken together, these limitations position the model as a heuristic tool to explore possible dynamics—not to predict specific outcomes. Its purpose is to surface potential mechanisms and trade-offs that merit further study

7.4 Future Research Directions

Building on the limitations discussed, there are many opportunities to extend and refine this work. Future research can improve the agent-based model's realism, incorporate richer data, and explore new questions that were beyond the current scope. This section outlines several promising directions for further investigation:

- Incorporate empirical behavioral data: A top priority is grounding the model's rules in real-world evidence. Future studies could collect or use *micro-level data* on household behavior in Cape Town – for example, surveys or interviews capturing why and how residents decide to move, what amenities they value, and how they respond to rent changes. Ethnographic insights or qualitative data could inform more nuanced rules (e.g. adding preferences for staying close to one's community or the role of social networks in relocation). Quantitative datasets, such as census migration flows, property transaction records, or mobile phone mobility data, could help calibrate movement patterns and destination choices. By learning from actual behavior, one could refine the decision algorithms (perhaps shifting from purely utility-based moves to rules that also account for social ties or perceived neighbourhood identity). In addition, empirical *willingness-to-pay* studies for green amenities (if available in the literature or via stated preference surveys) could provide better estimates for how much green space drives up demand (and thus rent). Incorporating these data-driven insights would make the agents' decisions less ad-hoc and improve the model's micro-foundations. Computational techniques like machine learning surrogates or Bayesian calibration could also be employed to systematically tune parameters so that the model outputs match observed patterns (e.g. matching historical gentrification trends if such data exist). Overall, data enrichment moves the model from a theoretical exercise closer to an empirically validated tool, increasing confidence in its simulations.

- Localize and validate key parameters: Alongside new data, future work should rigorously validate the model's key assumptions and parameters against Cape Town's context. For instance, the current model assumes a 2% rent increase following NbS upgrades; researchers could test this by conducting a hedonic price analysis on property values or rents in Cape Town, examining cases where green infrastructure was added (e.g. the creation of a park or greening of a facility) to see the actual price uplift. If evidence shows, say, a 5–10% increase in nearby property values after a major greening project, the model's assumption should be adjusted accordingly. Similarly, the assumed 4-month delay in rent change could be refined by looking at how quickly housing markets respond to neighbourhood improvements in practice. Spillover decay parameters (how far the impact of a greened patch extends) might be informed by spatial statistical analysis – e.g. measuring how property prices or environmental benefits taper off with distance from green sites. Other assumptions like the eviction risk function can be validated by comparing the model's implied eviction rates to any available housing eviction data or qualitative reports in Cape Town. By anchoring these parameters in empirical research, future models will shift from *stylized scenarios* toward evidence-based simulations. Such validation exercises not only improve model accuracy but also identify which assumptions are most sensitive or critical to outcomes. This could lead to more informed sensitivity analyses and help target which field data to collect. In sum, an iterative cycle of model refinement and local data validation would greatly strengthen the study – turning currently rough assumptions into grounded representations of Cape Town's socio-economic dynamics (Bressane, da Cunha Pinto, & de Castro Medeiros, 2024).

- Add political and community agency: One of the current model's stark omissions is the lack of resident feedback into policy. Future research should integrate political processes and collective action into the ABM. This could involve modeling residents or community groups as agents with the ability to influence outcomes. For example, an "activist agent" that can emerge when displacement reaches a certain threshold, organizing protests or pressuring the city to change course. The model could simulate scenarios where communities petition the government, resulting in a policy response (such as halting an NbS project, increasing public housing provision, or implementing rent controls). Likewise, the government actor in the model could be given a more dynamic role: rather than a fixed NbS implementation rule, the government could adapt its strategy based on indicators (perhaps slowing down greening in areas with high displacement, or shifting investments to avoid sensitive areas). Including such endogenous policy feedbacks would allow exploration of interventions that might mitigate green gentrification. For instance, one could test: *What if the city introduces an anti-eviction subsidy or stronger tenant protections after seeing early signs of displacement?* or *What if community resistance effectively blocks NbS in certain neighbourhoods?* Modeling these processes requires defining new rules (e.g. a probability of protest, or a threshold of displacement triggering policy change) and possibly new state variables (public opinion, political will, etc.), but it would greatly enrich the analysis. It moves the simulation toward a co-evolution of policy and community with the environment, reflecting the reality that cities are not passive backdrops, they are governed by people who can react and learn.

- Explicitly model diverse actors (developers, landlords, etc.): The current ABM treats institutions abstractly, but future versions could introduce *heterogeneous agent types* to represent key stakeholders in urban change. For example, a developer agent could be modeled, who makes decisions on where to buy property or build new housing. This agent might be attracted to neighbourhoods with rising livability or incoming high-income residents, thus accelerating development in greened areas. A landlord agent could own multiple housing units and decide how much to adjust rents based on market signals (potentially modeling profit-driven behavior like raising rents faster in NbS-enhanced areas). Non-governmental organizations or community land trusts could also be included as agents that attempt to preserve affordable housing or manage certain properties to prevent displacement. By simulating these actors, we capture the fact that gentrification is not just an aggregate market outcome but is driven by intentional decisions of powerful players (e.g. real estate investors). Their strategies (greed, altruism, compliance with or evasion of regulations) could be parameterized and tested. An agent-based approach is well-suited to include such multi-actor dynamics, and doing so would align the model more closely with urban theory that highlights the role of capital (developers/landowners) and community organizations in gentrification. It would also permit policy experiments like: what if nonprofit housing developers secure a portion of land and keep it permanently affordable, or how do private developers respond to different levels of green investment? These additions would make the simulation more complex but also more representative of the real system where government, private sector, and civil society interactions shape outcomes.

- Examine land tenure and housing diversity: Future research could improve the representation of housing tenure (renting vs. owning) and the variety of housing types. In the current model, all households essentially behave as renters (subject to rent increases and eviction). Introducing owner-occupiers would add an important dimension: owners typically benefit from neighbourhood greening (through rising property values) rather than facing eviction, but they might still experience indirect displacement pressures like increased property taxes or changing community fabric. Modelling owners vs. renters could show different distributional outcomes, e.g. greening might price out renters but enrich owners. Additionally, one could represent public or subsidised housing units, which might be insulated from market rent dynamics. A conceptually promising extension would be to simulate a social housing scenario—like that outlined in the City of Cape Town's Green Infrastructure and Social Housing strategies—where fixed-rent, publicly managed units offer long-term protection from displacement. Such agents could be made immune to rent hikes, helping assess how permanent affordability affects demographic stability and equitable access to NbS. Cape Town also includes informal settlements and historical townships where land markets function differently; incorporating these could be very insightful. The model could, for instance, allow certain patches or agents to be "immune" to rent hikes due to social policy (social housing), and explore how land ownership patterns (e.g., community vs. private-owned) influence gentrification trajectories.

- Higher-resolution spatial modeling: Increasing the spatial fidelity of the model is another clear direction. With better data, future studies could use actual GIS maps of Cape Town to create the environment. Instead of generic grid patches, one could use cadastral parcels or city blocks as agents or cells, each with its real-world attributes (population, current land use, etc.). Alternatively, a vector-based spatial ABM could represent households as points and buildings or parcels as discrete entities. This would allow the model to capture the fine-grained mosaic of urban land use – for example, distinguishing a patch of subsidised housing from an adjacent wealthy enclave, rather than averaging them. It also makes it easier to compare model output with observed data at the same scale (e.g. comparing simulated displacement on a particular street to known shifts in that area). The trade-off is that higher resolution increases computational complexity and data requirements. However, as data on cities improve and computing power grows, this step can greatly enhance realism. A more granular model could also incorporate spatial network infrastructure – e.g. actual road distances for commute calculations, or connectivity of areas by transit, which would improve how we model the attractiveness of locations (since right now distance to city center or jobs is not explicitly considered). Ultimately, moving toward a GIS-integrated ABM would help bridge the gap between the abstract simulation and the actual urban geography of Cape Town. It aligns with emerging practices in spatial ABMs that leverage detailed data for greater accuracy.

- Include social network and neighbourhood effects: To capture the social processes of gentrification, future models could integrate social networks among agents. People do not make moving decisions in isolation – they are influenced by friends, family, neighbors, and community networks. A network model could be overlaid where households are connected (ties could represent family relationships, friendships, or even co-workers). Through these ties, information and influence can flow: for example, hearing that relatives have moved to a suburb might encourage a family to follow, or conversely, strong community ties might discourage a household from leaving even if rents rise. One could implement peer effects such that if a certain fraction of a person's network moves out of the neighbourhood, that person's probability of moving increases (capturing a "community tipping point" phenomenon). Social networks can also affect *who moves in* – new residents might come via network connections of existing residents (which in reality can reinforce ethnic or class clustering). Incorporating these dynamics would require additional rules (and data, if possible, on typical social linkages in communities), but it would reflect the fact that gentrification has a cultural component: the decision to stay or go often involves community context, not just individual utility. In ABM research, network-driven behavior has been shown to yield different outcomes than purely atomistic decisions. Therefore, adding this layer could reveal nonlinear patterns (like sudden exodus of a community once a critical mass leaves, or, on the flip side, strong social cohesion resisting displacement longer than expected). Exploring network effects would deepen the model's sociological realism.

- Explore non-linear dynamics and tipping points: The current model is essentially linear in its progression (each tick, some actions happen given the rules), but real urban change can exhibit phase shifts or tipping points. Future research should experiment with the model to identify threshold effects. For example, is there a level of NbS coverage beyond which gentrification accelerates dramatically? The model could be used to simulate different intensities of greening interventions – from very minimal (only a few parks) to very extensive (city-wide greening) – to see if displacement rises proportionally or if there's a non-linear jump at some point.

Similarly, one could investigate *tipping points in displacement*: does the loss of a certain percentage of original low-income residents trigger a rapid neighbourhood turnover? Introducing feedback loops can create such non-linearities (for instance, as more high-income people move in, they attract even more high-income amenities, reinforcing desirability in a positive feedback). Future versions of the model might allow the attractiveness of patches to endogenously increase as they gentrify (beyond the NbS effect, e.g. a "trendiness" factor that grows once a critical mass of wealthy residents is present). This could produce self-reinforcing gentrification waves, which are often mentioned in urban theory. Conversely, the model could test interventions that aim to *break* these feedback loops (like policies that kick in once a neighbourhood's demographics change too fast). Probing these dynamics would provide insight into the stability of neighbourhoods: are there points of no return, or can early action prevent a complete turnover? Such experiments treat the ABM as a virtual lab to theorize about path dependence and momentum in urban social change.

Across all these future directions, the emphasis is on enriching the model to better reflect the complex reality of green gentrification, especially in a Global South context like Cape Town. The current study lays a foundation, demonstrating a framework for linking environmental improvements with social outcomes. Going forward, each extension – whether it's adding data, new agent types, or refined processes – can contribute to a more robust understanding. This line of research is part of a broader emerging literature on *just urban transitions*: how cities can pursue sustainability and climate resilience while safeguarding social equity (Wijsman & Berbés-Blázquez, 2022). By iteratively improving the model and incorporating insights from urban planning, sociology, and environmental science, future work can inform policies that strive for win-win outcomes (green cities that are also inclusive).

In conclusion, while the present model has clear limitations, it also opens up many productive avenues for research. Addressing those limitations will not only strengthen the model's validity but also deepen our theoretical and practical grasp of the intertwined environmental and social challenges facing cities like Cape Town in the push for sustainable development. The ultimate goal is to support urban policy and planning that *balances* ecological gains with the right to the city for vulnerable residents. Ensuring that "greening" does not inadvertently entrench inequality, but instead becomes part of a just urban future.

Chapter 8: Conclusions

8.1 Summary of Key Findings

The agent-based simulations indicate that implementing green infrastructure in the Cape Flats has markedly different outcomes depending on accompanying housing policies. In the unregulated Baseline scenario (incremental NbS with no affordability measures), neighbourhood greening dramatically increases demand and rents, especially Ward 57 area (≈25% rent rise over ten years), while Ward 79 sees a smaller increase. These market pressures trigger extensive displacement: thousands of low-income Coloured and Black African households are forced out (over 6,000 in Mitchell's Plain alone), replaced by wealthier White and Black African in-migrant households. In effect, livability and environmental quality do improve citywide, but only affluent newcomers reap those benefits – the original marginalised residents have largely departed. In contrast, Scenario 1 (mandatory inclusionary housing) markedly alters this trajectory. By reserving a percentage of new units at subsidised rents for low-income households, this policy caps rent inflation (citywide rent growth is limited to ≈18%) and maintains socio-economic diversity. In short, inclusionary zoning allows most original residents to stay and actually enjoy the improved conditions. Scenario 2 (targeted rent subsidies near NbS sites) also tempers displacement in the short term: rents stabilize and few households leave during the five-year subsidy period. However, once the subsidies end, displacement resumes and the neighbourhood begins to follow the Baseline pattern. Taken together, these results show that NbS alone tend to precipitate *green gentrification*, whereas coupling green projects with housing affordability measures can prevent or even reverse that process, aligning environmental upgrades with social equity.

8.2 Implications of the Research

The findings underscore that nature-based solutions are not inherently equitable. Instead, they must be embedded in a broader policy framework to avoid unintended harms. This study demonstrates that green infrastructure can easily become a catalyst for socio-economic exclusion unless paired with social interventions. Practically, urban planners in Cape Town (and similar cities) should anticipate these distributional effects: climate adaptation and greening projects should be designed hand-in-hand with housing equity measures. In other words, combining green infrastructure with social policy is critical for just and sustainable urban development. For example, the success of Scenario 2 suggests that inclusionary housing or permanent affordability mechanisms can ensure low-income communities benefit from resilience investments. The broader implication is that without deliberate equity safeguards, well-intentioned NbS can end up reinforcing historical inequalities rather than alleviating them. Thus, NbS planning must explicitly incorporate social considerations to meet sustainability goals without displacing vulnerable groups.

8.3 Answer to the Research Question

In response to the central research question: *"What are the distributional effects of implementing NbS in Cape Town?"*. The study finds that these effects hinge critically on housing policy context. Without policy intervention, NbS implementation alone predominantly benefits incoming higher-income residents and displaces low-income (historically marginalised) communities, thus exacerbating Cape Town's spatial inequities. However, when NbS are paired with inclusionary housing or subsidy policies, the distributional pattern shifts: environmental and livability gains are shared by existing residents. In short, NbS can either reinforce or mitigate inequality depending on social policy design. The simulation results imply that equitable distribution of NbS benefits is achievable, but only if green initiatives are deliberately integrated with housing and social supports.

8.4 Policy Recommendation

Consistent with these findings, a high-level recommendation for Cape Town's policymakers is to formally integrate affordable housing mandates into all climate adaptation and greening plans. For example, the City could adopt regulations requiring that any new park, wetland, or green infrastructure project be accompanied by dedicated affordable housing on-site or nearby – effectively operationalizing the inclusionary housing approach tested in the model. This aligns with the City's own draft policies (e.g. the 2018 Inclusionary Housing Policy that targets upgraded areas for affordable units) but calls for rigorous enforcement and expansion. In practice, the City's climate resilience strategies should allocate funding or mandates for subsidies and social housing in tandem with ecosystem projects. By mandating that nature-based interventions include a set-aside of low-cost units or rental assistance in the NbS zones, the City can help ensure that green improvements benefit current residents. Following are some concretised recommendations for the City Council.

First, the City should mandate the integration of affordable housing measures into all new green infrastructure projects. This can be operationalized through mechanisms such as inclusionary zoning, which would require that a significant proportion—ideally 30–50%—of new or redeveloped housing near NbS sites be reserved as permanently affordable units within mixed-income developments. In addition, conditional permitting processes could be introduced, whereby planning approvals for NbS interventions in gentrification-prone neighbourhoods are granted only if they are accompanied by credible, demonstrable commitments to protect or expand affordable housing stock in the surrounding area. To institutionalize this principle, the City's capital investment frameworks should embed spatial equity criteria, prioritizing green infrastructure upgrades in historically underserved areas and coupling these with parallel social investments, such as housing stabilization initiatives.

Second, policy mandates must be supported by concrete financial mechanisms and delivery tools to ensure lasting affordability. One option is to establish a "Green Equity Fund," which would allocate a portion of climate resilience or green infrastructure budgets to the development of affordable housing and rent stabilization programs in areas undergoing greening. This fund could be financed through developer levies, green municipal bonds, or public-private partnerships. Furthermore, geographically targeted rent vouchers or tax incentives for landlords could be introduced to help maintain below-market rents in NbS-adjacent areas, building on the temporary subsidies explored in Scenario 2 of this study. These interventions should aim for greater permanence or be tied to tenant tenure duration to enhance stability. The City could also support the establishment of community land trusts (CLTs) or municipal social housing entities tasked with acquiring and stewarding land around major NbS investments, thereby permanently delinking affordability from speculative land value increases.

Third, equitable outcomes require not only effective policy tools but also inclusive governance. The City should institutionalize participatory scenario planning within all NbS initiatives, ensuring that local communities—especially renters and residents of informal settlements—are involved in shaping both the design and management of green infrastructure projects. Community-led stewardship models, such as garden cooperatives or green roof collectives, can serve to build local agency and foster non-displacement-based forms of value generation from NbS. Finally, the City should establish an independent monitoring and redress mechanism, such as a green gentrification impact board or watchdog entity, to systematically track demographic, rent, and livability changes following NbS rollouts and intervene where inequitable patterns emerge.

8.5 Forward Outlook

In closing, this research returns to the original motivation: while nature-based solutions are vital tools for enhancing Cape Town's climate resilience, they are not inherently inclusive solutions. In a city shaped by an apartheid spatial legacy, resilience initiatives that ignore equity risk reinforcing the very patterns of segregation they seek to redress. The thesis underscores that if green infrastructure is pursued without attention to affordability and justice, it may simply "greenwash" historical inequalities. Instead, truly sustainable futures for the Cape Flats will depend on marrying ecological restoration with social justice, in a context specific manner. Moving forward, planners and communities must work together to ensure that NbS projects uplift rather than displace. Only by consciously designing NbS interventions to include affordable housing and participatory governance can cities like Cape Town achieve climate resilience that is both environmentally and socially sustainable.

Together, the previously presented recommendations offer a path toward more just and inclusive green transitions, ensuring that the benefits of urban greening do not come at the cost of displacement and deepened inequality. More broadly, Nature-Based Solutions policy must move away from one-size-fits-all approaches and embrace context-sensitive planning that responds to the socio-spatial realities of different communities. While it may be impractical for central authorities to design highly tailored NbS strategies at the level of individual wards or neighbourhoods, this does not preclude the development of adaptive frameworks that empower residents to co-shape solutions within their own contexts.

To address this, neighbourhood-level adaptation plans should be encouraged—grounded in principles of community self-reliance and social cohesion. These initiatives should be locally led but supported through public funding, technical guidance, and institutional scaffolding. Rather than prescribing top-down greening blueprints uniformly across all urban areas, such an approach allows for locally defined priorities, ensuring that NbS efforts are not only ecologically sound but socially responsive. By combining state-backed infrastructure investment with grassroots agency, this model fosters both environmental resilience and community ownership, particularly in historically underserved areas.

Ultimately, avoiding the reproduction of inequality through NbS will require governance models that are redistributive, participatory, and rooted in place, anchored not only in environmental metrics, but in the lived experiences and needs of those most vulnerable to displacement.

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Appendix A

Modelling Equations

Eviction Module

Affordability Ratio: The model computes the rent to income ratio for each household as: $ratio = \frac{Rent}{Income}$, which represents the fraction of income spent on housing. This ratio is used to determine affordability, and eviction risk.

Eviction probability : Eviction risk is modeled with a logistic (sigmoid) function of the affordability ratio relative to a threshold. Specifically,

$$risk = \frac{1}{1 + exp(-slope\ x\ (ratio\ - thr))}$$

where *slope* and *scale* are ward-specific parameters and *thr* is the model's eviction threshold. A random draw is then compared to risk × scale to decide if the household becomes vacant (evicted). Here, *slope* controls the steepness of the sigmoid response to affordability, and *thr* (eviction threshold) is the ratio at which eviction risk is 50%.

Long- Vacancy rent discount : If a house remains vacant for a long time, its rent is gradually discounted. In the code, after 12 time-steps of vacancy, there is a 10% chance each step to reduce rent by 2%:

$$r_{new} = 0.98\ x\ r_{old}$$

This ensures that unoccupied units become cheaper over time to encourage re-occupancy.

Market inflation

Monthly inflation factor: The model assumes an annual inflation rate annual_inflation_rate. It computes a per-timestep (monthly) multiplier:

$$m = (1 + annual\ inflation\ rate)^{1/12}$$

For example, with a 5% annual inflation, m=$1.05^{1/12}$≈1.00407. Each month, all rents are multiplied by this factor: the market's rent-per-area rates and all occupied household rents are updated by mmm.

Ward rent update: For each ward, the base market rent-per-square-meter is updated as

$$rent\ per\ m2_{new} = m\ x\ rent\ per\ m2_{old}$$

implementing inflation in the market. Concurrently, each household's current rent is increased by the same factor m during the step (if the household is occupied).

Household income growth

Income growth: Household incomes grow over time at a specified annual rate. The model computes a monthly income multiplier:

$$inc\ factor\ =\ (1\ +\ annual\ income\ growth)^{1/12}$$

In each time-step, every non-vacant household's income is multiplied by inc_factor. For example, with 0.5% annual growth, inc_factor≈$1.005^{1/12}$≈1.00041.

Pollution and Heat Decay

Environmental decay: Each patch has pollution and heat levels that decay over time. If a nature-based solution (NbS) is implemented on the patch, pollution and heat are reduced more aggressively:

$$pollution_{new}\ =\ 0.7\ x\ pollution_{old}$$
$$heat_{new}\ =\ 0.7\ x\ heat_{old}$$

otherwise they decay slower:

$$pollution_{new}\ =\ 0.98\ x\ pollution_{old}$$
$$heat_{new}\ =\ 0.98\ x\ heat_{old}$$

This is implemented each step for every patch. The 0.7 factor models rapid environmental improvement under NbS; 0.98 is a slower decay when NbS is not implemented.

NbS effects on Rent

Logistic rent growth: When an NbS patch becomes live, rents of its current occupants increase over time following a logistic-like curve (bounded by a carrying capacity CCC for that ward). Let *age* be the time since NbS implementation and *ramp* = min(age/delay,1). Then for a household with current rent rrr, the rent increment is computed as

$$\Delta r\ =\ r\ x\ \alpha\ x\ ramp\ x\ (\ 1 - \frac{r}{C}),$$

Where $\alpha\ =\ 0.03$ is a growth parameter and C is the ward's carrying-capacity rent. The household's rent is then updated as $r_{new}\ =\ r\ +\ \Delta r$. This ensures growth is small when rent is low (initially) and tapers off as rent approaches the cap.

Spatial Spillover: Nearby patches also experience rent increases due to proximity to an NbS patch. For a neighboring patch at distance ddd, the spillover factor is:

$$spill\ =\ \alpha\ x\ (1 - e^{-\gamma d}),$$

Where α and γ depend on the ward. Each household in the neighbourhood increases rent by this fraction:

$$r_{new} = r_{old} + min(spill, 0.20)\ x\ r_{old}$$

In code,
$spill = \alpha(1 - e^{-\gamma d})$, and cap = min(spill, 0.20), r + = r x cap. These equations model the diminishing spillover effects with distance.

Vacancy penalty and reletting

Vacancy penalty (piecewise linear): Each ward has vacancy-rate thresholds (LOW, HIGH) and corresponding maximum penalties (MAX_LOW, MAX_HIGH). Let v\nuv be the fraction of units vacant in the ward. The one-time penalty (discount) applied when a unit is re-rented is:

$$\text{penalty(v)} = \begin{cases} v\ x\ \frac{MAX\_LOW}{LOW}\ , v \leq LOW \\ MAX\_LOW + \frac{v - LOW}{HIGH - LOW}\ x\ (MAX\_HIGH - MAX\_LOW),\ LOW < v \leq HIGH \\ MAX\_HIGH,\ v > HIGH \end{cases}$$

This piecewise linear function (implemented in code) ensures the penalty grows from 0 when vacancy is low up to MAX_HIGH when vacancy exceeds HIGH.

Vacancy-duration rent adjustments: The model also applies one-off rent cuts or increases based on how long a unit has been vacant. If a vacant unit has been empty for exactly *cut_months* (3 months in Ward 57, for example), its rent is reduced by *cut_pct*:

$$r_{new} = (1 - cut\_pct)\ x\ r_{old}$$

If it has been empty for exactly *rebid_months* (6 months in Ward 57), the rent is increased by *rebid_pct*:

$$r_{new} = (1 - rebit\_pct)\ x\ r_{old}$$

These rules (e.g. –2% at 3 months, +1% at 6 months for Ward 57) are applied in adjust_rent_by_vacant_duration().

Liveability scoring & occupancy

Patch livability score: For each patch, the model computes a livability combining environmental quality, NbS presence, and occupancy ratio. First, define occupancy ratio

$$occupancy = \frac{occupied\ households}{initial\ households}$$

Then the patch livability is:

$$L_{patch} = 0.5\ x\ max\{0{,}100 - (5P + 3H)\} + 20\ x\ I_{NbS} + 10\ x\ occ,$$

Where P and H are the patch's pollution and heat levels, and I_{NbS} is 1 if Nb is implemented (else 0). This is implemented in the code as:

$$env\_score = max(0, 100 - (5P + 3H)), L = 0.5\, env\_score + 20\, I_{NbS} + 10\, occ$$

Overall liveability score: The city wide livabality score combines average environmental quality, NbS coverage, and pollution stability. Let $\underline{P}$, $\underline{H}$ be average pollution and heat. The environmental sunscore (out of 50) is:

$$S_{env} = 0.5\ x\ max\{0{,}100 - (5\underline{P} + 3\underline{H})\}$$

The NbS subscore (out of 30) is $S_{NbS} = 30\ x\ \frac{number\ of\ NbS\ patches}{total\ patches}$ and the stability subscore (out of 20) is $S_{stab} = 30\ x\ \frac{occupied\ households}{total\ households}$. The total livability then becomes: $S_{env} + S_{NbS} + S_{stab}$.

Prospective mover dynamics

Prospective mover target: The number of new movers each step depends on vacancy and liveability. Compute vacancy rate $\rho = \frac{vacancy\_count}{total\ households}$, then a vacancy factor $1 + 2\rho$. The livability factor is:

$$f = min\{ 3.0, max(0.5, \frac{liveability\_score}{50}\ x\ (1 + 2\rho))\}$$

The target number of movers is [base_prospectives×f]. This ensures more movers arrive when vacancy is high or liveability is high.

Appendix B

Simulation Outcomes

Rents Across Scenarios

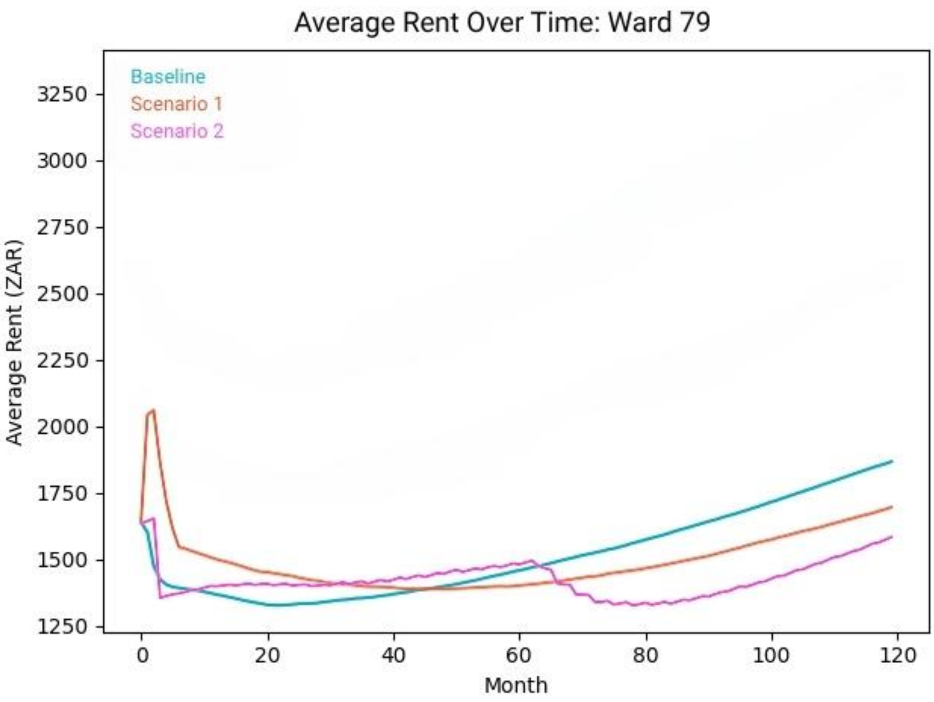

Figure b1: Avg Rent across Scenarios ward 79

Across all scenarios, Ward 79 shows an initial adjustment phase followed by a gradual rent climb. Scenario 1 (inclusionary reservations/discounts near NbS) begins with high rents but ends with an amount lower than the baseline. Scenario 2 (time-limited rent subsidies around NbS) finishes lowest, consistent with reduced cross-ward demand pressure when some near-NbS units remain accessible without requiring relocation. This pattern is consistent with the model's mechanism in which unlimited high-income in-movers and vacancy-linked rent updates transmit shocks across wards via the external applicant pool.

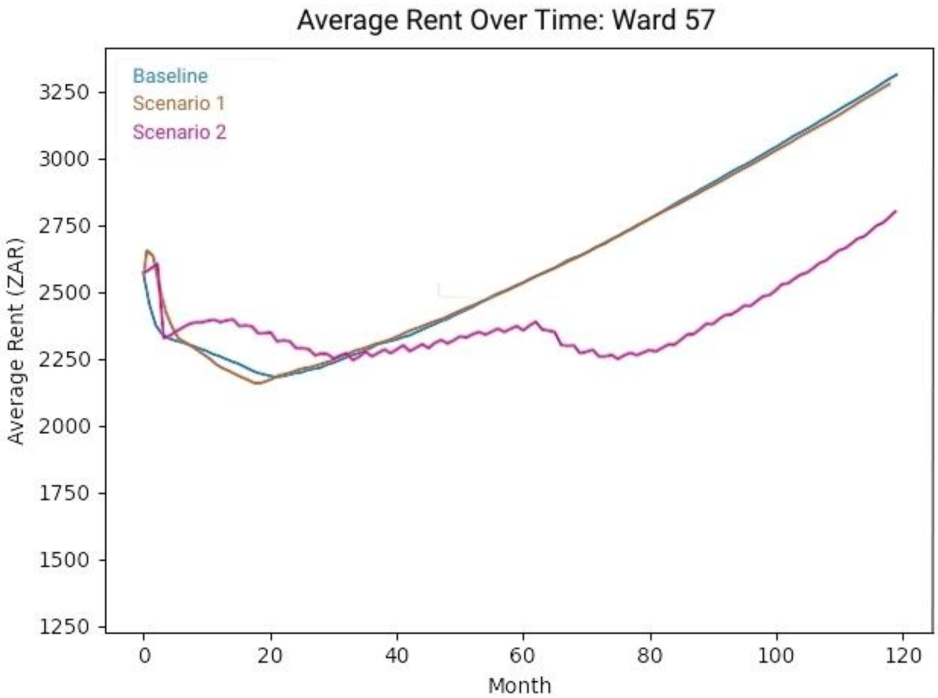

Figure b2: Avg Rent across Scenarios ward 57

In the higher-demand Ward 57, rents rise steadily in the baseline; Scenario 1 is similar, suggesting that a modest inclusionary share does not materially dampen aggregate rent growth when overall demand remains strong. By contrast, Scenario 2 attenuates rent escalation for most of the horizon; by the end, average rent is visibly below the baseline (≈15–20% lower). This aligns with the policy logic: targeted rent support near NbS blunts the price premium created by environmental upgrades and slows the feedback loop in which low vacancy accelerates rents. The early dip and subsequent rise reflect the vacancy discount followed by sustained demand from higher-income entrants as described in the rent-update and vacancy modules.

Rents Thresholds Across Scenarios

Baseline Scenario

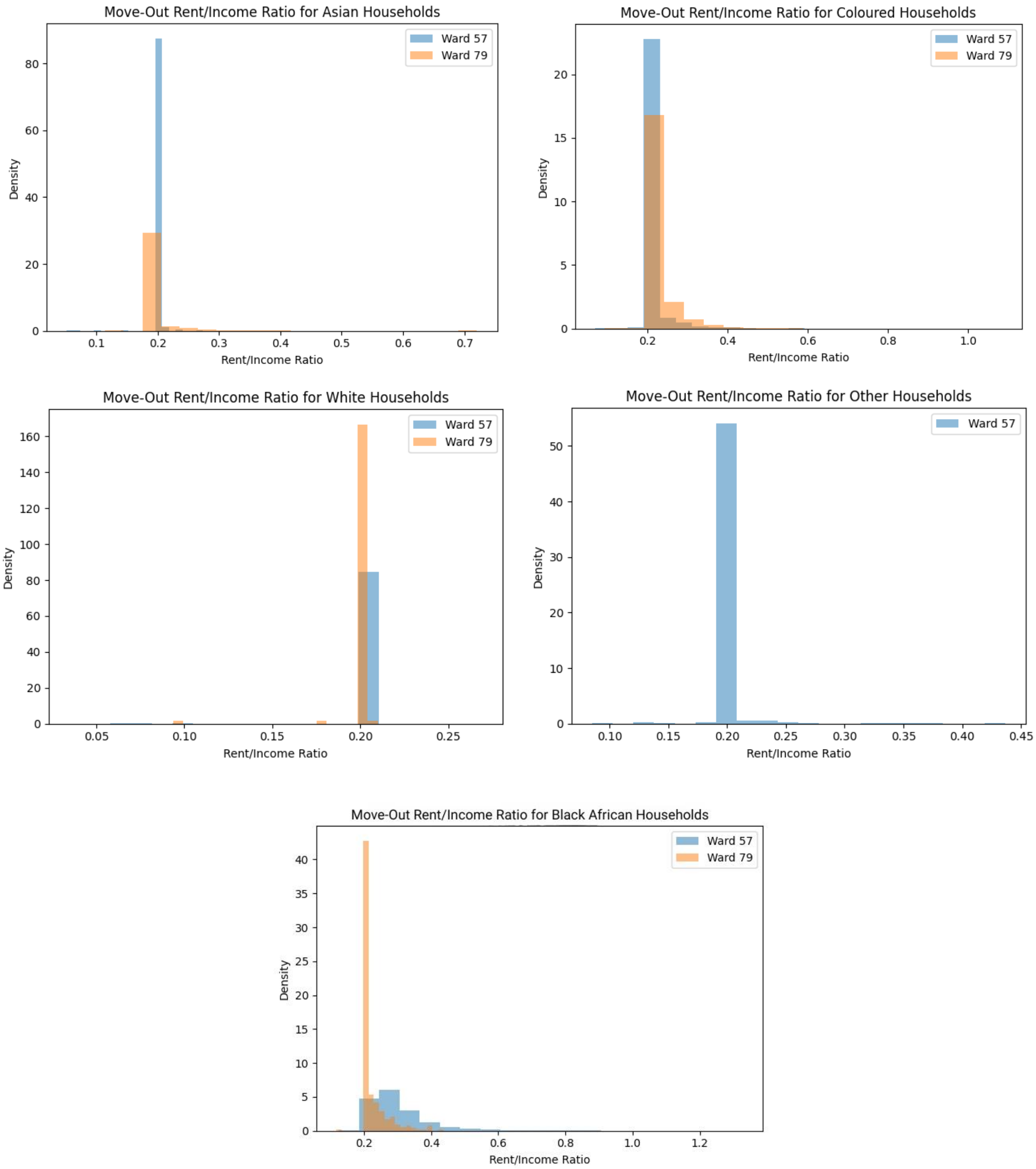

Figure b3: Rent Thresholds by Race for Baseline Scenario

Scenario 1

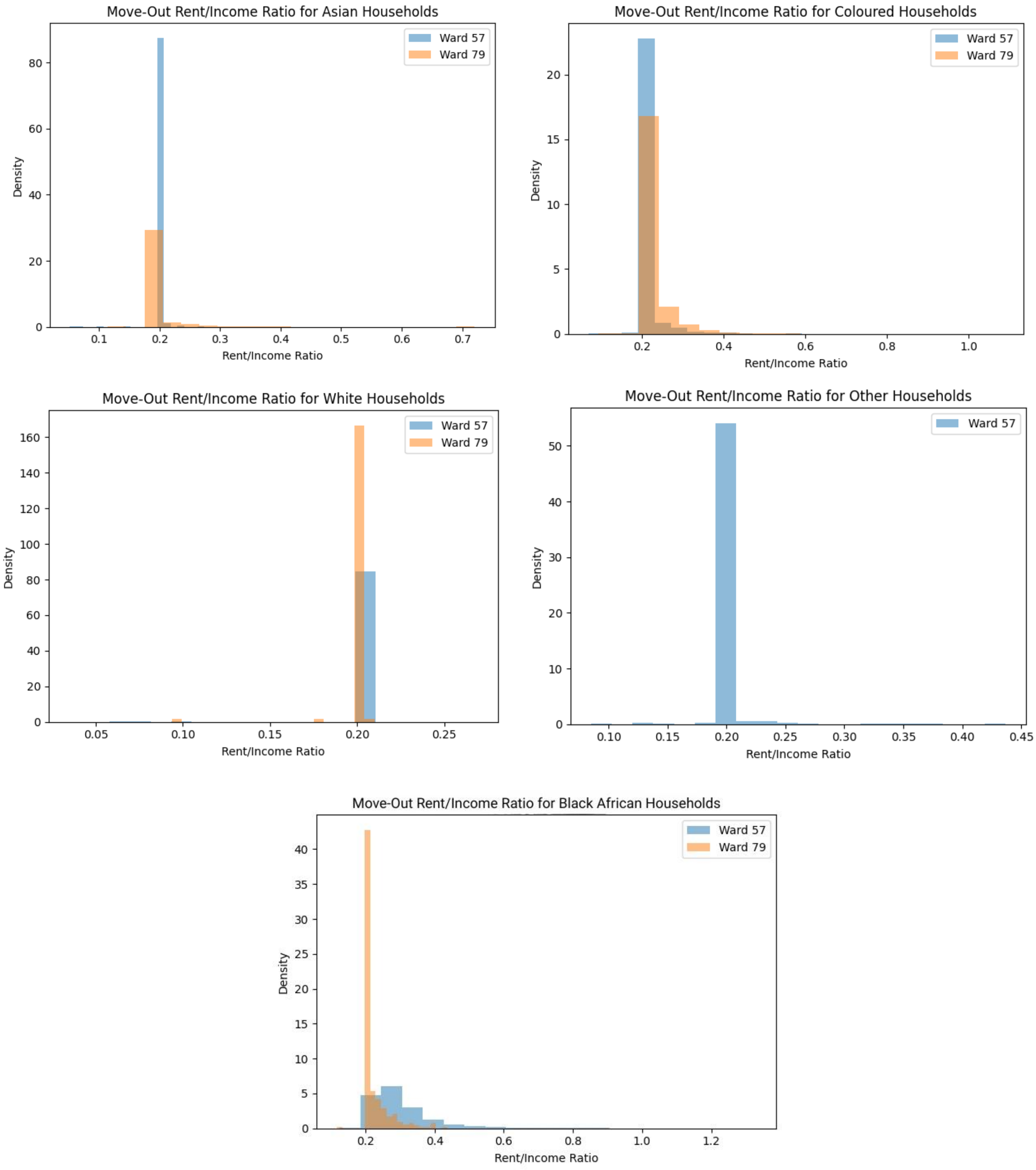

Figure b4: Rent Thresholds by Race for Scenario 1

Scenario 2

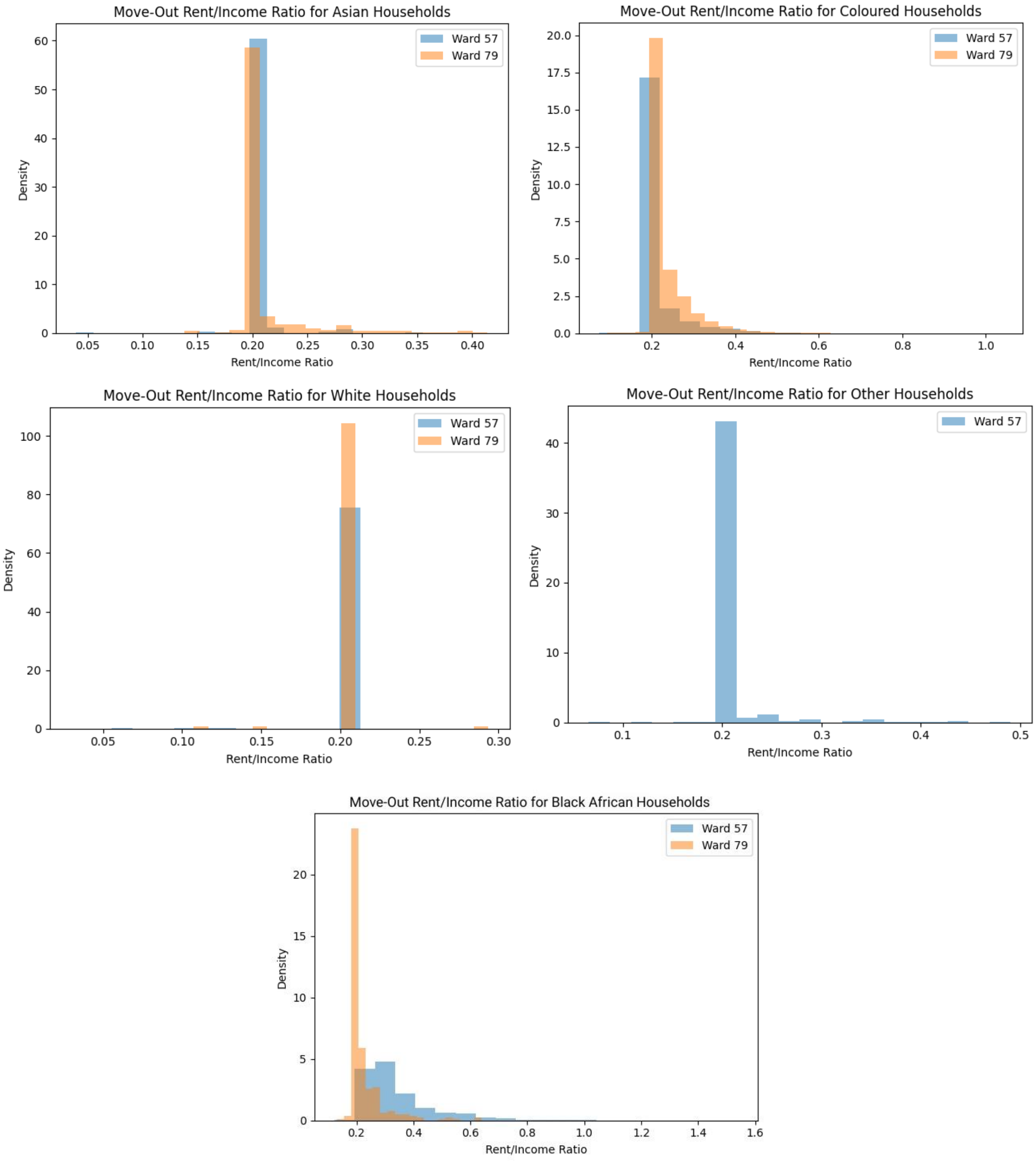

Figure b5: Rent Thresholds by Race for Scenario 2

Mover Incomes

Figure b6: Mover Incomes for Baseline Scenario

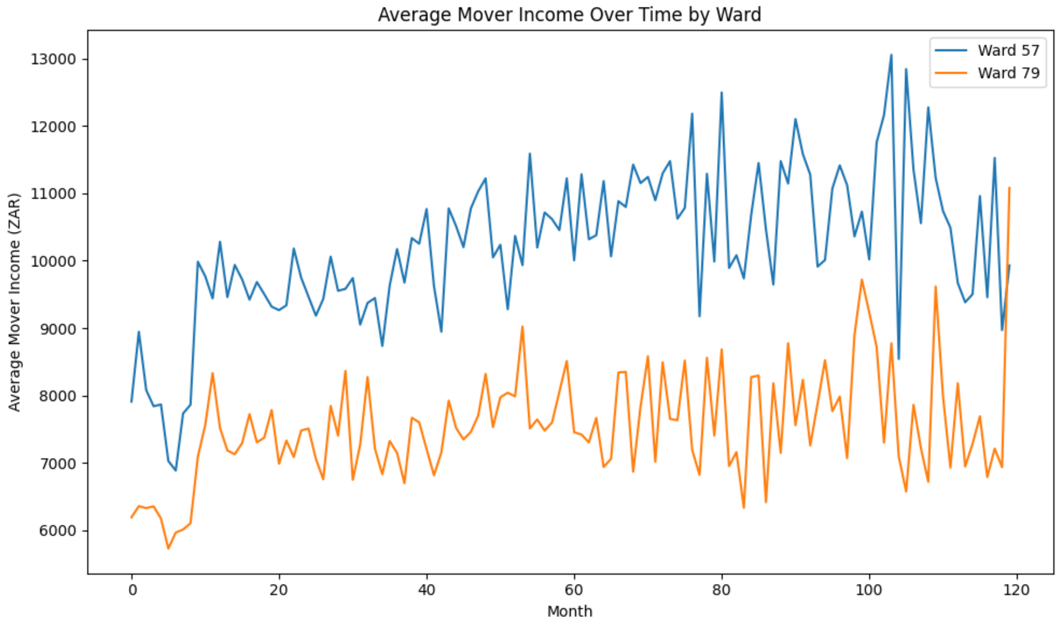

Figure b7: Mover Incomes for Scenario 1

Figure b8: Mover Incomes for Scenario 2

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