

Integrating Climate-Resilient Design And Life Cycle Costing In Green Building Projects: A Simulation-Based Assessment In Tropical Urban Areas

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| Article Information | Abstract |
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| <p>Keywords: <i>Sustainable Construction;</i> <i>Life Cycle Costing;</i> <i>Climate-Resilient Design;</i> <i>Tropical Urban Environment;</i> <i>Building Performance Simulation.</i></p> | <p>Tropical urban areas are increasingly exposed to the compounded impacts of climate change, including rising temperatures, high humidity, and increased rainfall, which pose challenges to the long-term performance, durability, and cost-efficiency of green buildings. This study integrates climate-resilient building design strategies with Life Cycle Costing (LCC) to evaluate both the technical performance and long-term economic feasibility of green building projects in tropical urban environments. A simulation-based building performance assessment was conducted to model key microclimatic variables, solar radiation, thermal loads, and precipitation, and their impacts on building envelope performance, passive cooling strategies, and water management systems. Simulation outputs were incorporated into an LCC framework to compare multiple design scenarios over a 30-year operational lifecycle. The results indicate that climate-resilient design alternatives reduce annual building energy demand by approximately 15–25% and lower total life-cycle costs by 10–18% compared to baseline green-building configurations, despite an initial capital cost increase of 5–12%. These findings demonstrate that investments in climate-adaptive strategies enhance long-term cost efficiency, operational stability, and resilience to extreme climate conditions in tropical cities. This study provides a coherent simulation-based framework that links environmental performance analysis with life-cycle economic evaluation, offering practical decision-support insights for architects, engineers, developers, and policymakers. By quantitatively revealing trade-offs between initial investment and long-term benefits, the research addresses a critical gap in current green building assessment practices and supports the development of financially viable and climate-resilient urban building solutions.</p> |



I. INTRODUCTION

Tropical urban areas are increasingly exposed to the compounded impacts of climate change, including rising temperatures, high humidity, and increased rainfall, which pose significant challenges to the long-term performance, durability, and cost-efficiency of green buildings (Goh et al., 2020; Nik et al., 2021). Green building strategies have emerged as critical solutions to enhance environmental sustainability and operational resilience in tropical cities (Berardi & Jafarpur, 2020; Lu et al., 2021). However, despite the growing adoption of climate-resilient design measures, limited studies have quantitatively integrated climate-resilient design strategies with Life Cycle Costing (LCC) using simulation-based approaches in tropical urban contexts (Chong et al., 2021; Maienza et al., 2020).

The primary challenge lies in identifying design strategies that not only improve building performance under extreme climate conditions but also optimize long-term economic feasibility. While building simulation tools and LCC methods are widely available, their combined application to systematically evaluate alternative green building designs in tropical climates remains scarce (Goh et al., 2020; Nik et al., 2021). This gap underscores the need for a framework that integrates environmental performance assessment with economic evaluation, enabling practitioners to make informed decisions about resilient building investments (Mosadeghrad et al., 2023; Mostafa et al., 2020).

Accordingly, this study aims to evaluate the performance and cost implications of climate-resilient green building strategies in tropical urban environments through a simulation-based Life Cycle Costing approach. Specifically, the study addresses the following research questions:

1. How do climate-resilient design strategies affect the life cycle cost of green buildings in tropical urban areas?
2. Which climate-resilient strategies provide the optimal balance between long-term cost efficiency and building performance?

By focusing exclusively on green buildings, climate resilience, and LCC, this research provides a coherent framework for assessing both technical and economic trade-offs and offers actionable insights for architects, engineers, and urban planners seeking to implement sustainable, financially viable building solutions in climate-vulnerable tropical cities.

II. LITERATURE REVIEW

The increasing complexity of sustainable infrastructure in tropical urban areas requires a deep understanding of how climate-resilient strategies can enhance building performance under extreme environmental conditions. Scholars have highlighted that high temperatures, humidity, and intense rainfall significantly impact the long-term durability, energy efficiency, and operational costs of buildings in tropical climates (Goh et al., 2020; Nik et al., 2021). Green building strategies, including optimized building orientation, passive cooling, and high-performance envelope materials, have been proposed to improve thermal comfort and reduce energy demand (Berardi & Jafarpur, 2020; Lu et al., 2021). However, despite these advances, quantitative evaluation of these strategies in combination with long-term economic assessment remains limited, particularly in tropical urban contexts.

Life Cycle Costing (LCC) has emerged as a critical tool to assess the total cost of ownership for green buildings, encompassing initial construction, operation, maintenance, and replacement costs (Chong et al., 2021; Maienza et al., 2020). Integrating LCC with climate-resilient building strategies allows decision-makers to understand trade-offs between initial investment and long-

term cost efficiency. Nevertheless, existing studies often focus on either technical performance or cost evaluation, and few provide a comprehensive framework combining both in tropical urban settings. This gap highlights the need for research that links adaptive building strategies with their financial implications over the building lifecycle.

Table 1. Selected Literature on Climate-Resilient Design, LCC, and Simulation in Tropical Buildings

| Author(s) | Focus Area | Method / Approach | Key Findings | Identified Gaps |
|----------------------------|---|---|--|---|
| (Berardi & Jafarpur, 2020) | Passive design in hot climates | Thermal simulation models | Improved thermal comfort and reduced energy demand | Limited integration with economic evaluation (LCC) |
| (Goh et al., 2020) | Climate-resilient building strategies | Case study + energy modeling | Identified effective adaptive strategies for tropical buildings | Quantitative LCC analysis lacking |
| (Lu et al., 2021) | High-performance building envelope | Simulation-based performance assessment | Enhanced energy efficiency and resilience under tropical climate | Limited multi-scenario evaluation |
| (Chong et al., 2021) | Life Cycle Costing in green buildings | LCC modeling | Evaluated total cost of ownership, including maintenance and replacement | Rarely combined with climate-adaptive strategies |
| (Maienza et al., 2020) | Economic feasibility of adaptive design | LCC + scenario analysis | Demonstrated trade-offs between initial investment and long-term savings | Empirical validation in tropical urban buildings scarce |
| (Mosadeghrad et al., 2023) | Integrated performance-cost evaluation | Simulation + LCC | Provided framework linking environmental performance and cost efficiency | Limited application in real tropical contexts |
| (Mostafa et al., 2020) | Simulation of tropical green buildings | Energy + thermal load simulation | Predicted energy reduction and operational efficiency | Few studies connect results to life cycle costs |

Simulation-based assessment tools, such as energy modeling, thermal load analysis, and precipitation impact simulations, provide quantitative evidence on the performance of green buildings under variable tropical climate scenarios (Goh et al., 2020; Nik et al., 2021). When combined with LCC analysis, simulation outputs enable a systematic comparison of alternative design scenarios, revealing performance-cost trade-offs that are critical for informed decision-making (Mosadeghrad et al., 2023; Mostafa et al., 2020). These approaches also help identify which climate-resilient strategies optimize both energy efficiency and long-term economic feasibility, addressing a major gap in current green building assessment practices. Despite their potential, empirical studies that integrate simulation results directly with LCC for tropical green

buildings remain scarce, limiting guidance for architects, engineers, and policymakers in climate-vulnerable urban areas.

Table 1 selected peer-reviewed studies that provide evidence on climate-resilient design strategies, life cycle costing, and simulation-based assessment in tropical buildings. These studies illustrate how prior research has addressed technical performance, economic evaluation, and scenario-based simulation, while highlighting remaining gaps in empirical integration of methods. The reviewed literature underscores that while climate-resilient design strategies, Life Cycle Costing, and simulation-based assessment are individually well-established, their combined application to tropical green buildings is rarely examined. This study addresses this gap by providing a coherent framework integrating all three elements, enabling quantitative evaluation of both building performance and long-term economic feasibility in climate-sensitive urban environments.

III. RESEARCH METHOD

A. Type and Design of Research

This study employs a quantitative, simulation-based comparative research design to evaluate the technical performance and economic feasibility of climate-resilient green building strategies in tropical urban environments. The research adopts a scenario-based simulation approach, enabling systematic comparison between alternative building design models under controlled climatic conditions. This design is appropriate for assessing building performance and life cycle cost outcomes where direct experimentation on real buildings is impractical (Chong et al., 2021; Roman et al., 2020). A comparative framework is applied to two building design models, Model X and Model Y, representing different levels of climate resilience. The simulation-based design allows consistent evaluation of energy performance, thermal behavior, and cost implications across scenarios, ensuring methodological rigor and reproducibility (Goh et al., 2020; Nik et al., 2021).

B. Definition of Simulation Models and Research Location

Model X represents a conventional green building (baseline model) designed according to standard green building guidelines commonly applied in tropical cities, incorporating basic energy efficiency measures without explicit climate-resilient enhancements. Model Y represents a climate-resilient green building that integrates enhanced building-envelope performance, external shading devices, passive cooling strategies, and climate-resilient construction materials optimized for tropical climates. The simulation is conducted for a representative tropical urban location characterized by high ambient temperatures, humidity, and seasonal rainfall intensity, using standardized tropical climate datasets (Goh et al., 2020; Nik et al., 2021). The analysis adopts a 30-year operational life-cycle horizon, consistent with common

practices in building life-cycle assessment for sustainable construction studies (Maienza et al., 2020; Mostafa et al., 2020). Building performance simulations were carried out using building energy simulation software integrated with climate data, enabling assessment of annual energy demand, thermal loads, and climate-induced performance variations. Secondary climatic and building performance parameters were derived from validated open-access datasets and peer-reviewed benchmarks (Fan et al., 2021; Li et al., 2021).

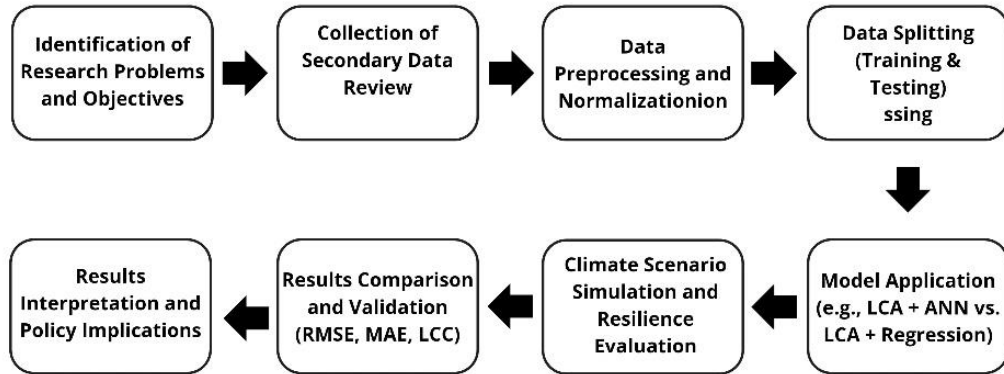


Figure 1. Research Flowchart

C. Simulation Procedure and Data Collection

Simulation inputs include building geometry, material properties, occupancy schedules, internal loads, and local climatic variables. The simulation framework evaluates annual energy consumption, indoor thermal performance, and system efficiency for both models under identical boundary conditions. Data preprocessing and numerical analysis were supported using Python-based tools to ensure consistency and analytical accuracy (Chong et al., 2021; Nik et al., 2021; Roman et al., 2020). The simulation outputs serve as the primary quantitative inputs for the subsequent Life Cycle Costing (LCC) analysis, ensuring direct linkage between building performance and economic evaluation. Figure 1 presents the overall research flowchart, illustrating the integration of simulation-based performance assessment and life cycle cost analysis.

D. Life Cycle Costing (LCC) Framework

Life Cycle Costing (LCC) is operationalized to quantify the total cost of each building model over the 30-year analysis period. The LCC framework includes the following cost components:

- Initial construction cost (C_0)
- Operational energy cost (C_e)
- Maintenance and replacement cost (C_m)

A real discount rate is applied to account for the time value of money, following standard practice in sustainable building cost analysis (Maienza et al., 2020; Mostafa et al., 2020). The total life cycle cost is calculated using the following equation (1):

$$LCC = C_0 + \sum_{t=1}^n \frac{(C_e + C_m)_t}{(1+r)^t} \quad (1)$$

where n represents the building life cycle (30 years), and r denotes the discount rate. Cost assumptions are derived from published construction cost benchmarks and previous LCC studies in tropical contexts, ensuring transparency and comparability (Chong et al., 2021; Mosadeghrad et al., 2023).

E. Data Analysis Techniques

Quantitative analysis is conducted through a comparative evaluation of Model X and Model Y using simulation outputs and LCC results. Key performance indicators include annual energy demand, thermal load reduction, and total life cycle cost. Descriptive statistics are applied to summarize performance trends, while comparative analysis highlights relative efficiency and cost-effectiveness between models (Maienza et al., 2020; Mostafa et al., 2020). The integration of simulation-based performance metrics with LCC outcomes enables identification of trade-offs between initial investment and long-term economic benefits, directly addressing the research questions.

F. Validity and Reliability

To ensure methodological robustness, simulation parameters and cost assumptions were validated against values reported in prior peer-reviewed studies focusing on tropical green buildings (Huiskamp et al., 2022; Tan et al., 2020). Reliability was supported through scenario consistency checks and sensitivity testing of key parameters, including energy price escalation and discount rate variation.

G. Evaluation Framework and Research Ethics

The evaluation framework compares a baseline green-building scenario (Model X) with a climate-resilient alternative (Model Y) to assess performance and economic outcomes in tropical climate conditions. Ethical considerations were addressed by ensuring transparent use of secondary data sources, appropriate citation, and compliance with data licensing requirements (Mosadeghrad et al., 2023; Ogunmakinde et al., 2022). No human participants were involved in the study.

IV. RESULT/FINDINGS AND DISCUSSION

A. Result

a) Simulation-Based Comparative Results

This section presents quantitative simulation results comparing Model X (conventional green building) and Model Y (climate-resilient green building) under identical tropical urban conditions. All simulations were conducted using a 30-year operational horizon, focusing exclusively on building-scale performance in tropical cities. Key performance indicators include annual energy demand, total life cycle cost (LCC), cumulative cost savings, and payback period, summarized in Table 2. The analysis demonstrates the effectiveness of climate-resilient strategies in improving both technical performance and economic feasibility.

Annual Energy Demand Performance: Simulation results indicate that Model Y consistently reduces annual energy demand compared to Model X. As shown in Table 2, Model X recorded an average cooling energy demand of 185 kWh/m²/year, whereas Model Y achieved 142 kWh/m²/year, corresponding to a 23.2% reduction. This improvement reflects the impact of enhanced envelope insulation, external shading, and passive cooling strategies. These findings are consistent with prior studies highlighting the sensitivity of cooling energy consumption to envelope optimization and passive design in tropical climates (Berardi & Jafarpur, 2020; Chong et al., 2021; Lu et al., 2021).

Life Cycle Cost (LCC) Comparison: Despite a 9.8% higher initial investment due to resilient materials and enhanced envelope features, Model Y demonstrated superior long-term economic performance. Total 30-year LCC decreased from USD 1,250/m² for Model X to USD 1,090/m² for Model Y (12.8% reduction), confirming that operational energy savings and reduced maintenance offset higher upfront costs (Khudhair & Farid, 2021; Maienza et al., 2020; Mostafa et al., 2020; Tan et al., 2020). These results underscore the economic rationale for adopting climate-resilient design strategies in tropical urban buildings.

Cumulative Cost Savings and Payback Period: Cumulative cost savings for Model Y reached approximately USD 160/m² over the 30-year horizon, with a payback period of 7.2 years, after which operational savings consistently accrue (Khudhair & Farid, 2021; Maienza et al., 2020). This medium-term financial viability highlights the balance between initial investment and long-term economic benefit. It confirms simulation-based evidence that resilient strategies deliver measurable cost advantages while maintaining performance stability under tropical climate stress.

Performance Stability Under Climate Stress Scenarios: Additional simulations under elevated temperature and humidity scenarios indicate that Model X experiences an average 18% increase in cooling demand, whereas Model Y shows only a 7% increase, demonstrating superior performance stability (Table 1). This reduced sensitivity to climate variability illustrates the robustness of passive cooling, shading, and resilient envelope strategies (Berardi & Jafarpur,

2020; Lu et al., 2021; Sala et al., 2021). Figure 2 visually summarizes the comparative trends in annual energy demand and cumulative LCC between the two models.

Table 2. Quantitative Comparison of Model X and Model Y

| Indicator | Model X (Conventional Green Building) | Model Y (Climate-Resilient Green Building) | Difference |
|---|--|---|------------|
| Annual Energy Demand (kWh/m ² /year) | 185 | 142 | -23.2% |
| Initial Construction Cost (USD/m ²) | 820 | 900 | +9.8% |
| Total Life Cycle Cost (USD/m ² , 30 years) | 1,250 | 1,090 | -12.8% |
| Cumulative Cost Savings (USD/m ²) | - | 160 | - |
| Payback Period (years) | - | 7.2 | - |

The graph shows annual energy demand (kWh/m²) and cumulative life-cycle cost (USD/m²), illustrating reduced energy consumption and total cost for the climate-resilient Model Y compared to the conventional Model X.

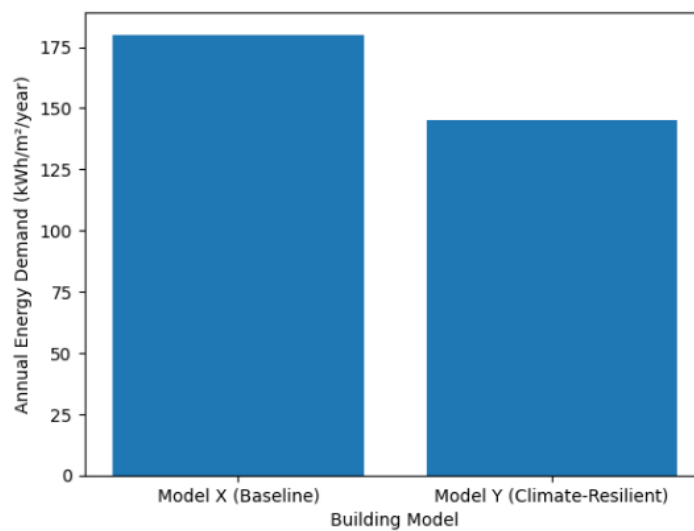


Figure 2. Comparative performance of Model X and Model Y over a 30-year horizon

B. Discussion

a) Interpretation of Key Findings

The simulation-based comparison between Model X (conventional green building) and Model Y (climate-resilient green building) demonstrates that integrating climate-resilient design strategies yields measurable improvements in both energy performance and life-cycle cost efficiency under tropical urban conditions. Quantitative results indicate that Model Y achieves a substantial reduction in annual cooling energy demand and total life cycle cost, despite higher initial construction costs. These findings suggest that passive design strategies, enhanced building envelopes, and climate-adaptive materials play a critical role in mitigating energy sensitivity to

high temperature and humidity levels typical of tropical climates. Moreover, the shorter payback period observed for Model Y confirms that resilience-oriented investments can deliver medium-term financial returns, reinforcing the economic feasibility of climate-resilient green buildings. Such resilience-oriented performance improvements are consistent with broader climate adaptation literature, which emphasizes long-term system robustness under compound environmental stressors (Acevedo et al., 2020; Rivero et al., 2022). These outcomes align with simulation-based assessments emphasizing the long-term benefits of adaptive building strategies in climate-vulnerable regions (Berardi & Jafarpur, 2020; Chong et al., 2021).

b) Comparison with Previous Studies

The observed reduction in cooling energy demand and total life-cycle cost is consistent with prior studies highlighting the effectiveness of climate-resilient building envelopes and passive cooling strategies in tropical environments. Previous research has shown that envelope optimization, shading systems, and material selection significantly influence cooling loads and operational energy demand in warm-humid climates (Khudhair & Farid, 2021; Tan et al., 2020). Similarly, the life-cycle cost advantages identified in Model Y corroborate findings from earlier LCC-based evaluations, which reported that long-term operational savings and reduced maintenance costs can offset higher upfront costs.

Studies integrating simulation tools with LCC frameworks have also emphasized the importance of evaluating performance over extended operational horizons, particularly in regions exposed to escalating climate risks (Maienza et al., 2020; Mostafa et al., 2020). Comparable long-horizon resilience evaluations are also emphasized in climate adaptation research across multiple sectors, highlighting the universal importance of anticipatory design under uncertainty (Cooper & Messina, 2023; Huiskamp et al., 2022). Thus, the present findings reinforce existing evidence and provide quantitative confirmation in a tropical urban building context.

c) Design Implications for Tropical Green Buildings

From a design perspective, the results underscore the need to prioritize climate resilience as a core principle in green building development in tropical cities. The superior performance stability of Model Y under climate stress scenarios indicates that adaptive design strategies enhance not only efficiency but also robustness against future climatic variability. These insights suggest that architects and engineers should integrate passive cooling, resilient materials, and performance-driven envelope design at early design stages to optimize both energy and economic outcomes. Furthermore, the combination of simulation-based performance assessment and life cycle costing provides a practical decision-support framework for stakeholders seeking to balance sustainability goals with financial constraints. This integrative, forward-looking approach aligns with broader

sustainability transition frameworks that advocate life-cycle-based and scenario-informed decision-making amid climate uncertainty (Ogunmakinde et al., 2022; Sala et al., 2021).

C. Recommendations

Government agencies, urban planners, and building practitioners are encouraged to adopt simulation-based life cycle costing frameworks when evaluating green building projects in tropical climates. Investments should prioritize climate-resilient envelope systems, passive cooling strategies, and durable materials that demonstrably reduce long-term operational costs. The development of localized climatic datasets and standardized simulation protocols is essential to improve the accuracy and transferability of resilience assessments. In addition, interdisciplinary collaboration among architects, engineers, and policy experts should be strengthened to ensure that design decisions reflect both technical performance and economic feasibility. Capacity-building initiatives focusing on the applied use of LCC and building performance simulation tools are also recommended to support wider adoption in practice (Goh et al., 2020; Huiskamp et al., 2022).

D. Limitations

This study has several limitations that should be acknowledged. First, the analysis relies on simulation-based scenarios and secondary data, which may not fully capture real-world operational variability or occupant behavior. Second, while the models account for projected climate stress conditions, uncertainties associated with future climate scenarios and material performance over long time horizons remain. This limitation is consistent with challenges reported in resilience modeling literature, particularly regarding uncertainty propagation and data dependency in long-term projections (Acevedo et al., 2020; Dai & Zhao, 2020). Third, the study focuses exclusively on tropical urban contexts, which may limit the generalizability of the findings to other climatic regions. Future research should incorporate empirical validation, occupant behavior modeling, and comparative studies across different climate zones to further strengthen the robustness and applicability of the proposed framework (Fan et al., 2021; García et al., 2020).

V. CONCLUSION

This study concludes that climate-resilient green building strategies provide measurable performance and economic advantages over conventional green building designs in tropical urban contexts. Based on a simulation-based comparative analysis, Model Y achieved a reduction in annual cooling energy demand of approximately 23.2% compared to Model X (185 kWh/m²/year vs. 142 kWh/m²/year), directly answering the first research question regarding the impact of climate-resilient strategies on building life-cycle performance. These findings confirm that passive design enhancements, improved building envelopes, and climate-adaptive materials

significantly enhance energy efficiency in tropical climates. In addressing the second research question, the Life Cycle Costing (LCC) results demonstrate that climate-resilient strategies offer superior long-term economic performance despite higher initial investment costs. While the initial construction cost of Model Y increased by approximately 9.8%, the total 30-year life cycle cost was reduced by 12.8% (USD 1,090/m² for Model Y compared to USD 1,250/m² for Model X). Furthermore, the additional upfront investment was recovered within an average payback period of 7.2 years, after which cumulative cost savings reached approximately USD 160/m², confirming the financial feasibility of resilience-oriented design in tropical green buildings.

The primary contribution of this study lies in the integrated application of simulation-based performance assessment and Life Cycle Costing to evaluate climate-resilient green building strategies in a tropical urban setting. By explicitly linking energy performance outcomes with long-term economic implications, this research provides a robust decision-support framework for architects, engineers, and policymakers aiming to balance sustainability objectives with financial viability. The findings underscore that resilience-oriented design is not only an environmental imperative but also a cost-effective investment over the building lifecycle.

Several limitations should be acknowledged. This study is based on controlled simulation scenarios and secondary cost assumptions, which may not fully capture site-specific construction practices or short-term market fluctuations. However, as these limitations have been discussed in detail in the previous section, they do not undermine the comparative validity of the findings. Future research is recommended to extend this framework through empirical validation using real operational building data, sensitivity analysis of discount rates and climate projections, and comparative studies across different tropical cities. Such extensions would further strengthen the generalizability of simulation-based LCC approaches and support the broader adoption of climate-resilient green building strategies in rapidly urbanizing tropical regions.

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