

Climate Change Resilience and Adaptation Initiatives and Programs: A Collection of Essays

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A Collection of Essays

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Climate Change Resilience and Adaptation Initiatives and Programs

A Collection of Essays

Introduction and Acknowledgments

INTRODUCTION

The Society of Actuaries Research Institute Catastrophe & Climate Strategic Research Program Steering Committee issued a call for essays to explore programs which build resilience against climate impacts, compare expected costs vs savings, measure how well programs perform, and highlight what was learned. The essay collection explores various approaches to investigating this topic and ways of evaluating the techniques described.

The six essays that form this collection are included below. The top three essays chosen for creativity, originality and the extent to which an idea might help promote further thought in this area, are noted here:

First Place Award	Applying Real Option Theory to the Evaluation of Climate Adaptation Investments Xinyi (Cindy) Hu, ASA, MAAA
Second Place Award	A Quantitative Framework to Evaluate the Effectiveness of Climate resilience and Adaptation Programs Sathiya Livingston
Third Place Award	Leveraging Artificial Intelligence and Actuarial Techniques to Strengthen Climate Change Resilience and Adaptation Programs Jeniffer Nasike Atetwe, BSc (Actuarial Science)

Thank you for your interest in this essay collection. We welcome your feedback via the survey banners embedded in this document.

THE CALL FOR ESSAYS

BACKGROUND AND OVERVIEW

In 2024, 27 disasters in the United States resulted in damages exceeding \$1 billion. These disasters included two winter storms, one wildfire event, one drought/heatwave event, one flooding event, six tornado outbreaks, 11 severe weather/hail events and five hurricanes. The most costly of these events was Hurricane Helene, which resulted in 219 deaths and cost \$79.6 billion¹, and the 2025 wildfires in Los Angeles were extremely costly, as well. Outside the United States, Cyclone Chido killed more than 1,000 people, a heatwave in Bangladesh impacted 33 million people and a drought in Columbia has had a significant impact on the economy there².

Many organizations and individuals are committed to minimizing the impact of and building resilience against events like these and countless less dramatic ones. Examples of such efforts include:

- Louisiana strengthened its building codes following Hurricane Katrina.³
- New York City implemented the Be a Buddy program in 2018 which is designed to connect volunteers with vulnerable populations to help them find resources, like cooling spots, during a heat emergency.⁴
- In Florida, there are efforts to build hurricane-proof communities. One such community, Hunter's Point, was able to withstand the effects of Hurricane Helene.⁵

Of course, before implementing an adaptation initiative or program to enhance resilience, a decision-maker will have to address several questions before its launch, such as:

- "What are the expected direct costs and off-setting savings?"
- "How will this impact the target population?"

After the fact, key questions include "How well did the initiative perform relative to expectations?" and "What can we learn from this process?"

The purpose of this call for essays is to provide actuaries and others with a better understanding of the underlying conditions leading to the need for resilience and adaptation initiatives, examples of such programs, an overview of quantitative techniques for evaluating such programs, a framework for decision-making, and recommendations for future research.

SCOPE

Although the primary focus of this call for essays is climate-related risks, essays on catastrophes or other practice areas are welcome.

TOPICS OF INTEREST

The SOA Research Institute (SOA) invites essay submissions addressing climate change resilience and adaptation initiatives and programs. This call has been intentionally framed in broad terms to encourage a wide range of perspectives and approaches. Contributors may explore one or more of the sample topics listed below or propose alternative specific subjects that fall within the overall theme and scope. The examples provided are illustrative, neither comprehensive nor exhaustive.

Sample topics include:

- A typology describing the range of current resilience and adaptation programs and initiatives globally
 - Case studies on implemented programs and initiatives
 - The use of AI in the decision-making process
 - Techniques for identifying potential programs
 - Discussions on quantitative techniques for evaluating programs, such as the XGBoost model, the pre/post method, the participant/non-participant method, and discounted cash flow analysis using real option theory
 - Practical applications in actuarial work
-

¹ [2024: An active year of U.S. billion-dollar weather and climate disasters | NOAA Climate.gov](#)

² [2024 climate weather disasters outside united states - Search](#)

³ [Louisiana moves to upgrade building code in wake of Katrina - Business Insurance](#)

⁴ [Be a Buddy - NYC Mayor's Office of Climate and Environmental Justice](#)

⁵ [Helene and Milton put this net-zero, hurricane-proof community to the test. The lights stayed on as everything else went dark | CNN](#)



1st Place Award Winner

Applying Real Option Theory to the Evaluation of Climate Adaptation Investments

Xinyi (Cindy) Hu, ASA, MAAA

Any views and ideas expressed in the essays are the author's alone and may not reflect the views and ideas of the Society of Actuaries, the Society of Actuaries Research Institute, Society of Actuaries members, nor the author's employer.

INTRODUCTION

Climate change has introduced unprecedented levels of uncertainty into the frequency, severity, and geographic distribution of extreme weather events (IPCC, 2021). Hurricanes, floods, heatwaves, droughts, and wildfires increasingly impose large and volatile costs on insurers, governments, and communities (Swiss Re Institute, 2025). In response, climate adaptation investments (also known as actions designed to reduce vulnerability and enhance resilience) have become a critical component of climate risk management. These investments include infrastructure upgrades, strengthened building codes, early warning systems, and community-based resilience programs.

Evaluating climate adaptation investments poses significant challenges. Traditional cost-benefit analysis (CBA), often based on discounted cash flow (DCF) methods, struggles to accommodate deep uncertainty, non-linear risk escalation, and managerial flexibility. Decisions are typically treated as irreversible, even though adaptation strategies can often be staged, expanded, delayed, or abandoned as conditions evolve.

Real option theory offers a powerful enhancement to conventional evaluation methods by explicitly valuing flexibility under uncertainty (Hayes, 2025). Actuaries, with their expertise in probabilistic modeling, long-term valuation, and risk management, are well positioned to apply real option techniques to climate adaptation decisions. This essay explores how real option theory can improve the evaluation of climate adaptation investments in an actuarial context, discusses practical modeling approaches, and highlights implications for actuarial practice.

LIMITATIONS OF TRADITIONAL DISCOUNTED CASH FLOW ANALYSIS

Discounted cash flow analysis is a widely used tool for evaluating long-term investments. Under a DCF framework, expected future costs and benefits are projected and discounted to present value using a specified discount rate (Fernando, 2025). While this approach provides a clear structure, it has notable limitations when applied to climate adaptation.

First, climate risks evolve dynamically and non-linearly. Hazard frequency and severity can increase progressively with warming, while crossing biophysical or adaptation limits may lead to rapidly escalating risks and impacts (IPCC, 2023). Deterministic projections used in standard DCF analysis may fail to capture these dynamics.

Second, under a standard DCF framework, investment value is assessed using a single forecast of expected future cash flows and a fixed discount rate, which does not explicitly account for decision flexibility over time (Fernando, 2025). In reality, adaptation investments are often incremental. For example, flood defenses can be built in stages, and building standards can be progressively strengthened. Ignoring this flexibility may lead to suboptimal conclusions, such as either overinvesting too early or underinvesting in the face of future risk escalation.

Third, uncertainty is typically handled through sensitivity testing rather than explicitly modeled as stochastic. This approach underrepresents tail risk and provides limited insight into downside outcomes—an issue of particular concern for actuaries focused on solvency, capital adequacy, and extreme events (Townsend, 2022).

These limitations motivate the use of alternative frameworks capable of valuing uncertainty and flexibility more rigorously.

OVERVIEW OF REAL OPTION THEORY

Real option theory extends financial option pricing concepts to real (non-financial) investments. A real option represents the right, but not the obligation, to take a particular action in the future, such as expanding, delaying, scaling back, or abandoning a project, in response to new information (Dixit & Pindyck, 1994).

Unlike financial options, real options are embedded in physical assets or policy decisions and are not traded in markets. Their value arises from managerial flexibility under uncertainty. Common types of real options include:

- Option to defer an investment until uncertainty is reduced
- Option to expand capacity if conditions worsen or demand increases
- Option to contract or abandon if outcomes are unfavorable
- Staged investment options, where decisions are made sequentially

Climate adaptation investments naturally lend themselves to real option analysis because climate uncertainty evolves over time and learning occurs as new data become available.

THEORETICAL FRAMEWORK: REAL OPTIONS VS. DISCOUNTED CASH FLOW

DISCOUNTED CASH FLOW AS A STATIC VALUATION FRAMEWORK

Discounted cash flow (DCF) analysis evaluates an investment by computing the expected present value of future net benefits. Formally, the net present value (NPV) of an adaptation investment is given by

$$NPV_0 = \mathbb{E} \left[\sum_{t=0}^T \frac{B_t - C_t}{(1+r)^t} \right],$$

Where B_t and C_t denote benefits and costs at time t , respectively, and r is the discount rate. The standard DCF decision rule is to invest immediately if $NPV_0 > 0$.

This framework implicitly assumes that the investment decision is made once, at the outset, and that the investment is irreversible. Uncertainty enters only through expected values or deterministic sensitivity

analysis applied to model inputs. As a result, DCF reduces the decision problem to a comparison of mean outcomes, abstracting from the timing of decisions, learning over time, and the distribution of outcomes.

These assumptions are particularly restrictive for climate adaptation investments, where uncertainty is persistent, information improves over time, and decisions can often be staged or adjusted as risks evolve.

STOCHASTIC INVESTMENT UNDER UNCERTAINTY

Real option theory reframes investment as a dynamic decision made under uncertainty. Rather than assuming that benefits are known with certainty, the value of an adaptation investment, such as avoided climate damages, is modeled as a stochastic process. A common representation assumes that the underlying benefit process V_t follows a geometric Brownian motion:

$$dV_t = \mu V_t dt + \sigma V_t dW_t,$$

where μ is the expected growth rate of benefits, σ measures volatility, and W_t is a standard Brownian motion. Volatility here reflects uncertainty in climate outcomes, including changes in hazard frequency, severity, and exposure.

Let I denote the irreversible cost of undertaking the adaptation investment. The decision-maker holds an option to invest and chooses the optimal timing to exercise this option. Under real option theory, the value of the investment opportunity, denoted $F(V)$, satisfies the Bellman equation:

$$F(V) = \max\{V - I, \mathbb{E}[e^{-r\Delta t} F(V_{t+\Delta t}) | V_t = V]\}.$$

This expression captures the tradeoff between exercising the option immediately (and receiving net payoff $V - I$) and waiting for additional information. Solving this problem yields an optimal investment threshold V^* such that investment occurs only when $V_t \geq V^*$, where

$$V^* = \frac{\beta}{\beta - 1} I, \quad \beta = \frac{1}{2} - \frac{\mu}{\sigma^2} + \sqrt{\left(\frac{\mu}{\sigma^2} - \frac{1}{2}\right)^2 + \frac{2r}{\sigma^2}}.$$

Because $\beta > 1$, it follows that $V^* > I$. This result has a critical implication: even when the expected net present value is positive, it may be optimal to delay investment. The gap $V^* - I$ represents the option value of waiting.

INCREMENTAL ADAPTATION AS A COMPOUND OPTION

Many climate adaptation investments are not single, all-or-nothing decisions but rather sequences of incremental actions. Examples include staged flood defenses or progressively strengthened building codes. Real option theory models such strategies as compound options, where each stage creates the option, but not the obligation, to proceed to the next stage.

Let $F_t(V_t)$ denote the value of holding the option at stage t . Then

$$F_t(V_t) = e^{-r\Delta t} \mathbb{E}_t[\max(0, F_{t+1}(V_{t+1}) - I_{t+1})]$$

With terminal condition:

$$F_T(V_T) = \max(V_T - I_T, 0)$$

where I_{t+1} is the cost of next-stage investment. This recursive structure explicitly captures learning and sequential decision-making. In contrast, DCF typically collapses staged investments into a single expected cash flow stream, thereby ignoring the informational and strategic value of staging.

DISTRIBUTIONAL RISK AND TAIL OUTCOMES

Finally, DCF focuses on expected values, whereas real option analysis naturally accommodates distributional concerns. Climate-related losses are often heavy-tailed, and downside outcomes are particularly relevant for actuaries concerned with solvency and capital adequacy.

Within a real options framework, valuation can be extended to incorporate risk-sensitive criteria, such as tail risk measures:

$$Value = \mathbb{E}[X] - \lambda * TVaR_{\alpha}(L), L = -X$$

Where X represents net outcomes and $TVaR_{\alpha}$ captures extreme losses beyond a specified confidence level. The ability to delay, scale, or abandon investments reduces exposure to extreme downside scenarios—an effect that DCF, which collapses outcomes to a single expected value, cannot represent.

OPTION TO EXPAND UNDER ESCALATING CLIMATE RISK

When climate damages may escalate rapidly, the ability to expand protective measures represents a valuable real option. Let V_t denote avoided damages from an expanded adaptation measure at time t , and suppose

$$\frac{dV_t}{V_t} = \mu dt + \sigma_t dW_t$$

where σ_t captures uncertainty in future climate outcomes. Let K denote the expansion cost. The payoff from expansion is

$$\max(V_t - K, 0)$$

so, the value of the option to expand is

$$\mathbb{E}[\max(V_t - K, 0)].$$

Under standard real option assumptions, option value is increasing in volatility:

$$\frac{\partial}{\partial \sigma_t} \mathbb{E}[\max(V_t - K, 0)] > 0.$$

This result reflects the asymmetric payoff structure of real options. Higher uncertainty increases the likelihood of high-damage realizations in which expansion yields substantial benefits, while unfavorable outcomes are bound by the decision not to exercise the option.

Climate change is expected to increase both the expected level of climate-related damages (μ) and their volatility (σ_t). Consequently, the value of retaining expansion flexibility rises not only with higher expected damages, but also with greater uncertainty, which widens the distribution of possible outcomes. In this sense, adaptation investments embed an exposure to uncertainty analogous to positive volatility sensitivity in financial options: greater uncertainty enhances the value of waiting and responding conditional on realized outcomes.

From an actuarial and risk-management perspective, this logic aligns with established practice. Instruments whose payoffs respond positively to tail risk are valued for their role in managing extreme losses, supporting capital adequacy, and preserving solvency. Real option analysis thus provides a rigorous framework for valuing flexibility in climate adaptation decisions under increasing uncertainty.

INTUITIVE EXAMPLES: WHY FLEXIBILITY HAS VALUE

Climate adaptation decisions are rarely one-time, irreversible commitments. Instead, they often involve adaptive pathways. For example, a coastal municipality may initially construct moderate flood defenses while retaining the option to heighten them if sea-level rise accelerates. Similarly, insurers may invest in improved risk modeling or loss mitigation incentives, with the option to expand programs as climate risks become clearer.

EXAMPLE 1: THE VALUE OF WAITING

Real option theory captures the value of waiting and learning. Under high uncertainty, delaying irreversible investments can be optimal, even when expected net present value is positive.

Consider a city deciding whether to build a flood barrier at cost $I = 110$ (million dollars). Once completed, the barrier permanently prevents flood damage, but construction requires one year. Annual flood damage depends on the underlying climate regime, which is uncertain at time $t = 0$ but is revealed at the end of Year 1 based on observed losses. With equal probability $\pi = 0.5$, the city may face a high-risk climate state with annual damages $D_H = 24.2$, or a low-risk state with annual damages $D_L = 6.05$. The city discounts future costs and benefits at rate $r = 10\%$.

If the city invests immediately at $t = 0$, it pays the cost I upfront. Because construction takes one year, the barrier becomes operational in Year 2, so only damages for $t \geq 2$ are avoided. Let

$$PV_{t=0}(D_s, t \geq 2)$$

denote the discounted present value of avoided damages from Year 2 onward under climate state $s \in \{H, L\}$, evaluated at time $t = 0$. Using the damage streams implied by the annual losses above, these values are

$$PV_{t=0}(D_H, t \geq 2) = 220$$

$$PV_{t=0}(D_L, t \geq 2) = 55.$$

The net present value of immediate investment in each state is therefore

$$NPV_{t=0}(D_H, t \geq 2) = 220 - 110 = 110$$

$$NPV_{t=0}(D_L, t \geq 2) = 55 - 110 = -55$$

Taking expectations across climate states yields the standard discounted cash-flow valuation:

$$\mathbb{E}[NPV_{t=0}] = 0.5(110) + 0.5(-55) = 27.5.$$

Under traditional DCF rules, the city would invest immediately because the expected net present value is positive.

Now suppose instead that the city has the option to wait until $t = 1$ before deciding whether to invest. By the end of Year 1, realized flood damages reveal whether the climate state is high-risk or low-risk. If the

high-risk state is observed, the city builds the barrier at $t = 1$. Because construction still requires one year, flood damages are avoided only for $t \geq 3$. The discounted value of avoided damages in this case is

$$PV_{t=0}(D_H, t \geq 3) = 200,$$

implying a net present value (measured at $t = 0$) of

$$NPV_{t=0}(D_H, t \geq 3) = 200 - \frac{110}{1.1} = 100.$$

If the low-risk state is observed, the city optimally chooses not to invest, because avoided damages from $t \geq 3$ would equal

$$PV_{t=0}(D_L, t \geq 3) = 50.$$

This amount is insufficient to justify the construction cost $I = \frac{110}{1.1} = 100$ evaluated at $t = 0$, so the city exercises its option not to build. The realized payoff in the low-risk state is therefore zero rather than negative.

The expected value of the wait-and-see strategy is thus

$$\mathbb{E}[NPV_{t=0}^{\text{wait}}] = 0.5(100) + 0.5(0) = 50.$$

Comparing this to the value of immediate investment, the option value of waiting can be expressed as

$$\text{Option Value} = \mathbb{E}[NPV_{t=0}^{\text{wait}}] - \mathbb{E}[NPV_{t=0}] = 50 - 27.5 = 22.5.$$

This option value arises because waiting preserves flexibility. Immediate investment forces the city to commit irreversibly before uncertainty is resolved, exposing it to the risk of overinvestment in the low-risk state. By delaying the decision, the city sacrifices some avoided damages in the high-risk state due to the construction lag but gains the ability to condition the investment on newly revealed information. Traditional discounted cash-flow analysis overlooks this trade-off because it treats investment as both immediate and irreversible. Real option theory makes explicit that, under uncertainty, the ability to wait and learn has economic value—even when the expected net present value of immediate investment is already positive.

EXAMPLE 2: INCREMENTAL ADAPTATION BEATS ALL-AT-ONCE INVESTMENT

Consider two alternative strategies for flood protection:

1. Build a large barrier now at a cost of \$220 million.
2. Build a smaller barrier now for \$80 million, with the option to expand later for an additional \$140 million if flood risk increases.

Assume:

- Flood risk escalates with 40% probability.
- If risk escalates, total avoided damages from a large barrier are \$300 million.
- If risk does not escalate, avoided damages are only \$100 million.

Under traditional DCF, the expected avoided damages:

$$0.4 * 300 + 0.6 * 100 = 180.$$

The Net Present Value is

$$NPV_{large} = 180 - 220 = -40.$$

Under traditional DCF analysis, the project is rejected because the expected net present value is negative. The city would conclude that flood protection is not economically justified.

However, under the staged strategy, the city makes a modest initial investment and retains the option to expand protection if flood risk increases.

In the high-risk scenario (40% probability), flood damage escalates substantially. The city expands the barrier, incurring total costs of \$220 million (initial investment plus expansion), while avoiding \$300 million in damages. The resulting net payoff is \$80 million.

In the low-risk scenario (60% probability), flood risk remains moderate. The city does not expand the barrier, incurring only the initial \$80 million cost and avoiding \$100 million in damages, yielding a net payoff of \$20 million.

Weighing these outcomes by their probabilities gives an expected net present value of

$$0.4 \times 80 + 0.6 \times 20 = 44.$$

Therefore, the staged, flexible strategy delivers a positive expected NPV of \$44 million. This result highlights how flexibility improves outcomes across both scenarios by avoiding unnecessary investment while preserving protection against severe risk.

ACTUARIAL MODELING OF REAL OPTIONS IN ADAPTATION INVESTMENTS

Stochastic modeling of climate risk is a foundational step in applying real option theory to adaptation investments. Actuaries can use stochastic climate scenarios to represent a wide range of plausible future hazard pathways. These scenarios are informed by climate science and catastrophe models and may reflect changes in the frequency, severity, and geographic distribution of extreme events (IPCC, 2023; Geneva Association, 2021). Instead of producing a single expected outcome, each scenario generates a distribution of potential future losses and benefits, providing the probabilistic structure required for real options analysis.

This probabilistic framework is critical because real options valuation depends on understanding uncertainty and flexibility over time. By capturing the range of possible climate outcomes, actuaries can better evaluate how adaptation investments perform under different conditions and assess the value of making decisions dynamically as new information emerges.

A variety of techniques are available to value real options in climate adaptation settings. Decision trees and binomial lattice models represent investment decisions at discrete points in time, with branches reflecting alternative future states. These approaches are intuitive and particularly well suited to staged or phased infrastructure investments where decisions can be revisited as uncertainty resolves (Brandão, Dyer, & Hahn, 2005).

Monte Carlo simulation offers a more flexible approach by modeling uncertainty continuously rather than at discrete intervals. This method is especially valuable when multiple risk drivers interact and is well aligned with actuarial practices commonly used in capital modeling and reserving. Dynamic programming

provides another powerful tool, enabling the identification of optimal decision rules across time and supporting the analysis of complex, multi-stage adaptation pathways (Dixit & Pindyck, 1994).

The selection of an appropriate valuation method depends on the complexity of the investment, the quality and availability of data, and computational constraints. Actuaries need to balance analytical rigor with practical considerations to ensure that real options analyses are both robust and usable for decision-making.

ADVANTAGES OVER TRADITIONAL APPROACHES

Real option theory provides several important advantages over traditional discounted cash flow (DCF) analysis when assessing climate adaptation investments. One of its key strengths is the explicit valuation of flexibility. Rather than treating flexibility as a qualitative consideration or ignoring it altogether, real option theory recognizes managerial and strategic flexibility as an asset that can add measurable value to an investment.

Another major advantage is its improved treatment of uncertainty. By relying on stochastic modeling, real option analysis aligns closely with actuarial best practices and allows for a more complete understanding of risk, including tail risk and extreme outcomes. This is particularly relevant in the context of climate change, where uncertainty and low-probability, high-impact events play a critical role.

Real option theory also enhances decision-making around the timing of investments. Instead of focusing solely on whether an investment should be made, it helps determine when it is optimal to invest, defer, expand, or abandon a project as conditions evolve. This dynamic perspective is especially valuable for adaptation measures that can be staged over time.

Finally, the real options framework aligns well with risk-based decision-making. It supports evaluations that consider not only expected value but also downside risk and volatility, which are central concerns for actuaries. Together, these strengths make real option theory particularly well suited for actuaries advising insurers, governments, and infrastructure stakeholders on climate adaptation strategies.

IMPLICATIONS FOR ACTUARIAL PRACTICE

Applying real option theory to climate adaptation investments expands the actuarial role beyond traditional pricing and reserving. In property and casualty insurance, real option analysis can inform decisions about underwriting strategies, risk mitigation incentives, and capital deployment in climate-exposed regions. In public-sector and infrastructure contexts, actuaries can support long-term investment planning under deep uncertainty.

Furthermore, real option thinking aligns closely with enterprise risk management (ERM), where flexibility, stress testing, and adaptive strategies are central themes. As climate risk increasingly influences financial stability, actuaries equipped with real option tools can provide valuable guidance to decision-makers.

CHALLENGES AND FUTURE RESEARCH

Despite its advantages, real option analysis faces practical challenges. Data limitations, model complexity, and computational demands can hinder implementation. Additionally, translating climate science into probabilistic financial inputs remains an evolving area of research.

Future work could focus on developing standardized actuarial frameworks for real option valuation in climate adaptation, improving integration with catastrophe models, and exploring regulatory applications.

Enhanced collaboration between actuaries, climate scientists, and policymakers will be essential to advance this field.

CONCLUSION

Climate adaptation investments are essential for managing the growing risks associated with climate change. Traditional evaluation methods, while useful, often fail to capture the value of flexibility under uncertainty. Real option theory provides a robust framework for enhancing cost–benefit analysis by explicitly valuing adaptive decision-making.

Actuaries are uniquely equipped to apply real option techniques, combining stochastic modeling, long-term valuation, and risk management expertise. By incorporating real option theory into the evaluation of climate adaptation investments, actuaries can support more resilient, efficient, and forward-looking decisions in an increasingly uncertain climate future.

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2nd Place Award Winner

A Quantitative Framework to Evaluate the Effectiveness of Climate Resilience and Adaptation Programs

Sathiya Livingston

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ABSTRACT

As climate change reshapes hazard patterns, resilience and adaptation programs have become increasingly important instruments for managing climate-related risk. Yet despite accelerating investment, these programs are rarely evaluated using tools capable of translating physical or social benefits into actuarially meaningful outcomes. This essay advances a quantitative framework that conceptualizes adaptation not as a discrete policy achievement, but as a transformation of loss distributions over time. By anchoring evaluation in probabilistic risk metrics, the framework enables consistent assessment of whether adaptation initiatives reduce expected losses, dampen volatility, compress tail risk, or improve systemic stability.

The framework integrates baseline risk characterization, exposure normalization, climate-adjusted counterfactual construction, and post-implementation distributional analysis, culminating in financial metrics directly relevant to pricing, reserving, and capital adequacy. Rather than privileging single-event performance, it emphasizes distributional shifts and tail behavior, reflecting the realities of climate-driven non-stationarity.

Beyond providing an evaluation tool, the framework reframes the role of actuaries in climate resilience. It positions actuarial science as a discipline capable of bridging climate science, public policy, and financial decision-making through transparent treatment of uncertainty. By focusing on measurement, comparability, and learning, this essay aims to stimulate thought on how adaptation effectiveness can be evaluated, refined, and embedded within risk management.

INTRODUCTION

Climate change has moved decisively from a distant environmental concern to a present and measurable financial risk. Insurers now confront losses that are not only larger on average, but also more volatile, more correlated, and less predictable than historical experience would suggest. Governments face growing fiscal exposure from disaster response, infrastructure repair, and social disruption, while households and firms experience increasing instability in livelihoods and asset values. In this environment, climate resilience and adaptation programs have emerged as essential complements to mitigation efforts, seeking not to prevent climate change itself, but to limit its economic and social consequences.

Yet as investment in adaptation accelerates, a critical problem persists: there is no widely accepted way to measure whether these programs actually work from a risk perspective. Evaluations frequently emphasize engineering thresholds, implementation milestones, or qualitative narratives of preparedness. While valuable, such approaches do not translate easily into the language of financial risk, capital adequacy, or long-term sustainability. As a result, adaptation initiatives are often compared incompletely, funded inconsistently, and incorporated unevenly into insurance and financial decision-making.

This measurement gap matters because climate risk is fundamentally probabilistic. Losses emerge from distributions, not single events, and the most consequential impacts often reside in the tails rather than the averages. An intervention that leaves expected losses largely unchanged may still be profoundly valuable if it reduces extreme outcomes, dampens volatility, or interrupts cascading failures. Without tools capable of capturing these effects, adaptation effectiveness is systematically underappreciated or misunderstood.

Actuarial science is well suited to address this challenge. The profession has long specialized in evaluating interventions under uncertainty by examining how they reshape loss distributions, alter tail behavior, and influence capital requirements. Applying this perspective to climate adaptation reframes the central question. The issue is not whether a program functions as designed, but whether it transforms risk in a way that is durable, measurable, and decision relevant. This essay takes that question as its starting point and develops a framework intended to make adaptation effectiveness visible in actuarial terms. By doing so, it seeks to move adaptation debates beyond advocacy and anecdote, toward structured learning grounded in evidence. The framework does not promise certainty, but it offers a disciplined way to compare options, recognize trade-offs, and improve decisions over time as climate risks continue to evolve and guide future actuarial research, professional standards, and cross-sector collaboration under deep uncertainty in coming decades globally and locally.

What remains largely unexamined, however, is a foundational assumption embedded in many adaptation evaluations: that effectiveness is primarily observable through project performance or average outcomes. This assumption obscures the principal financial value of many adaptation programs, which lies not in eliminating losses, but in reshaping volatility, tail risk, and loss correlation under non-stationary climate conditions. By reframing adaptation as a transformation of loss distributions rather than a project outcome, this essay challenges prevailing evaluation practices and proposes a framework better aligned with actuarial decision-making under uncertainty.

CONCEPTUAL FOUNDATIONS: ADAPTATION AS RISK TRANSFORMATION

A persistent obstacle to evaluating climate adaptation lies not in data alone, but in how adaptation is conceptually framed. Adaptation initiatives are commonly treated as discrete projects: a seawall is constructed, a cooling center is opened, or a zoning regulation is revised. Success is then assessed by asking whether the project performs its intended function. While this logic is appropriate for engineering validation or program management, it is insufficient for understanding financial risk under uncertainty.

From an actuarial perspective, adaptation should instead be understood as a **risk transformation mechanism**. The relevant question is not whether an intervention works in isolation, but how it reshapes the statistical behavior of losses over time. This includes changes in frequency, severity, volatility, dependence, and tail behavior. Framing adaptation in this way shifts attention from individual events to distributions, from isolated performance to systemic effect.

This distinction matters because many adaptation programs are designed explicitly to manage extremes rather than averages. A flood defense system may reduce the probability of catastrophic inundation while leaving moderate losses largely unaffected. A heat adaptation program may not alter average mortality or

claims materially yet significantly reduce losses during rare but severe heatwaves. Evaluations focused on mean outcomes or single-event thresholds risk missing precisely the impacts that matter most for solvency, capital adequacy, and long-term stability.

Risk transformation also highlights the temporal dimension of adaptation. Climate change introduces non-stationarity into hazard processes, meaning that the risk environment evolves over time even in the absence of intervention. Adaptation effectiveness therefore cannot be assessed at a single point. It must be evaluated relative to a changing baseline, asking whether the intervention alters the trajectory of risk rather than merely offsetting current conditions.

Finally, conceptualizing adaptation as risk transformation clarifies the role of actuarial judgment. Uncertainty is unavoidable, attribution is imperfect, and data are often limited. Yet actuarial practice has long operated under such constraints by making assumptions explicit, testing sensitivity, and focusing on decision relevance rather than false precision. Treating adaptation as a probabilistic modification of loss behavior places it squarely within this tradition. It allows effectiveness to be discussed not as a binary outcome, but as a matter of degree, trade-offs, and confidence. In doing so, it creates a foundation for structured learning, comparison across programs, and cumulative improvement in how societies manage climate-related financial risk over time.

DEFINING EFFECTIVENESS AND DESIGN PRINCIPLES

Once adaptation is understood as a mechanism of risk transformation, the notion of “effectiveness” can be defined in actuarially meaningful terms. Effectiveness is not a binary judgment, nor is it synonymous with technical success. Instead, it reflects the extent to which an intervention measurably alters the financial risk profile faced by insurers, governments, or communities under uncertainty.

This framework defines effectiveness along four primary dimensions. First, **expected loss impact** captures whether an adaptation program reduces average annual losses over a relevant horizon. Second, **volatility impact** assesses whether the intervention dampens variability in outcomes, stabilizing earnings, and fiscal flows. Third, **tail risk impact** examines changes in extreme outcomes, measured through tail-sensitive metrics such as Value-at-Risk or Tail Value-at-Risk. Fourth, **systemic stability impact** evaluates whether the program reduces correlation, clustering, or cascading failures across space or time.

These dimensions recognize that adaptation programs may generate value in different ways. Some interventions primarily reduce routine losses, while others provide protection against rare but devastating events. A program should not be judged ineffective simply because its benefits concentrate in one dimension rather than another. Instead, trade-offs should be made explicit and evaluated against decision objectives.

To operationalize these concepts, the evaluation framework is guided by five design principles. **Comparability** ensures that results can be meaningfully contrasted across programs and hazards. **Transparency** requires assumptions, data limitations, and uncertainty to be clearly stated. **Decision relevance** anchors metrics to financial and risk management needs. **Flexibility** allows application under varying data conditions. Finally, a **dynamic orientation** acknowledges that climate risk is evolving rather than stationary. Together, these principles ensure that effectiveness evaluation supports learning and informed decision-making rather than retrospective justification.

THE QUANTITATIVE FRAMEWORK STRUCTURE

The purpose of the framework is not to produce precise forecasts of future climate losses, but to enable structured comparison, learning, and prioritization under uncertainty. Its central premise is that adaptation

effectiveness should be evaluated through changes in the shape and stability of loss distributions, rather than through isolated event performance or static engineering thresholds.

The proposed framework evaluates climate resilience and adaptation programs through a structured sequence of analytical steps. Each step addresses a specific challenge inherent in measuring adaptation effectiveness under uncertainty, while remaining grounded in actuarial practice. The steps are designed to be applied sequentially, though iteration is encouraged as new data or insights emerge.

The first component is **baseline risk characterization**. This step establishes the pre-adaptation risk environment by constructing probabilistic loss distributions using historical claims data, catastrophe models, or scenario-based simulations. Adjustments for inflation, exposure growth, and reporting practices are essential to ensure internal consistency. Importantly, the baseline should capture not only expected losses but also higher moments of the distribution, including variance, skewness, and tail behavior. The purpose is not to predict future losses precisely, but to define a coherent reference against which change can be measured.

The second component is **exposure and vulnerability normalization**. Observed losses are influenced by changes in population, asset values, construction practices, and demographic composition. Without normalization, increases in exposure may obscure genuine risk reduction, while exposure declines may falsely suggest adaptation success. Normalization adjusts losses to a common exposure basis, allowing observed changes to be more plausibly attributed to the adaptation program rather than external growth effects.

The third component is **incorporation of climate-driven risk trends**. Climate change introduces non-stationarity into hazard processes, meaning that historical averages are no longer reliable guides to future risk. The framework therefore incorporates assumptions about changing hazard frequency or severity, either deterministically or probabilistically. These assumptions should be applied consistently across baseline and counterfactual scenarios and subjected to sensitivity testing, as results may depend strongly on trend magnitude.

The fourth component is **counterfactual construction**. Because the world without the adaptation program cannot be observed, a plausible counterfactual must be constructed. This may involve extrapolating historical trends, benchmarking against comparable regions without intervention, or simulating losses using hazard-vulnerability models. Rather than relying on a single counterfactual, the framework encourages consideration of a range of plausible scenarios to test robustness.

The fifth component is **post-implementation outcome analysis**. Observed losses following implementation are compared against baseline and counterfactual distributions. The emphasis is on distributional shifts rather than individual event performance. A program may fail during an extreme event yet still deliver substantial long-term risk reduction. Examining changes in dispersion and tail thickness captures such effects more effectively than event-level analysis.

The sixth component is **risk and economic impact measurement**. Changes in loss distributions are translated into actuarially relevant metrics, including expected loss, volatility, tail risk measures, and capital requirements. Where appropriate, economic valuation techniques such as discounted cash flow or cost-effectiveness ratios may be applied to relate risk reduction to program cost.

The final component is **uncertainty and robustness assessment**. All results should be accompanied by sensitivity analysis reflecting parameter uncertainty, model structure, and counterfactual assumptions. Rather than undermining conclusions, this transparency enhances credibility and supports learning.

Together, these components form a flexible yet disciplined framework for evaluating adaptation effectiveness in actuarial terms.

Quantitative evaluation methods, such as difference-in-differences analysis, participant/non-participant comparisons, or model-based approaches informed by machine learning, can complement the probabilistic framework presented here by supporting counterfactual construction and robustness testing under data constraints.

ILLUSTRATIVE APPLICATIONS: FLOOD AND HEAT ADAPTATION

To illustrate how the framework operates in practice, consider two stylized adaptation contexts: coastal flood mitigation and urban heat adaptation. The following examples are illustrative and stylized, and do not represent empirical findings from a specific jurisdiction, dataset, or implemented program. These examples are simplified but realistic, and they highlight how different programs may deliver value through distinct risk dimensions.

In the first case, a coastal region implements a flood adaptation program combining levee reinforcement, drainage upgrades, and revised land-use regulations. Historical loss data show increasing flood-related claims driven by sea-level rise and storm surge. Baseline modeling projects continued growth in both expected losses and tail risk. A counterfactual scenario extrapolates these trends in the absence of intervention.

Following implementation, observed losses exhibit mixed signals. Moderate flood losses continue to occur, and a severe storm still produces material damage. However, distributional analysis reveals a meaningful compression of the extreme tail. Tail Value-at-Risk declines substantially relative to the counterfactual, even though expected annual loss falls only modestly. Capital modeling indicates reduced solvency strain under extreme scenarios, suggesting that the program's primary value lies in stabilizing catastrophic risk rather than eliminating routine losses. An evaluation focused solely on averages would understate this benefit.

The second case involves an urban heat adaptation program incorporating reflective surfaces, expanded green space, targeted cooling centers, and public warning systems. Historical data show rising heat-related mortality and insurance claims during extreme temperature events. Baseline analysis projects increasing volatility rather than a steady rise in average losses.

Post-implementation outcomes show little change in mean losses, leading some observers to question program effectiveness. However, applying the framework reveals a different picture. The frequency of extreme loss years declines, loss variance decreases, and tail risk measures improve relative to the counterfactual. While average outcomes remain similar, the distribution becomes more stable, reducing the likelihood of years with severe fiscal or insurance strain.

Together, these examples illustrate why distributional evaluation is essential. Adaptation programs often deliver their greatest value by reshaping tails and volatility rather than averages. The framework makes these effects visible, enabling decision-makers to recognize benefits that would otherwise remain hidden and to compare programs based on how they transform risk, not merely on how they perform in isolated events.

IMPLICATIONS, LIMITATIONS, FUTURE RESEARCH, AND CONCLUSION

The framework proposed in this essay has implications that extend beyond individual adaptation programs. By translating resilience into actuarially meaningful risk transformations, it enables adaptation to be

incorporated into pricing, reserving, capital allocation, and enterprise risk management. This integration allows insurers and public institutions to move from viewing adaptation as an external policy concern to treating it as a measurable component of financial sustainability. It also creates a basis for comparing diverse interventions using a common risk language, improving prioritization under constrained resources.


Several limitations must be acknowledged. Data availability is uneven, attribution is inherently imperfect, and long time horizons complicate validation. Behavioral responses, institutional change, and social feedback effects are difficult to model yet may influence outcomes materially. In addition, climate non-stationarity introduces structural uncertainty that cannot be eliminated through refinement alone. These limitations do not invalidate quantitative evaluation, but they require transparency, humility, and continuous reassessment.

Future research can strengthen the framework in several directions. Dynamic updating as new data emerge, integration of machine learning techniques for counterfactual construction, and development of standardized metrics for cross-program comparison all warrant exploration. Collaboration between actuaries, climate scientists, engineers, and policymakers will be essential to refine assumptions and improve robustness.

In conclusion, as climate adaptation plays an increasingly central role in managing climate-related risk, the ability to evaluate its effectiveness quantitatively becomes increasingly valuable. By treating adaptation as a transformation of risk distributions rather than a symbolic or project-level achievement, this framework reframes how effectiveness itself is defined, offering a disciplined way to learn what works, compare alternatives, and improve decisions over time under deep and evolving uncertainty. Within the scope of this conceptual framework, the analysis is intended to inform measurement and comparison rather than to prescribe specific policy actions or implementation choices.

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3rd Place Award Winner

Leveraging Artificial Intelligence and Actuarial Techniques to Strengthen Climate Change Resilience and Adaptation Programs

Jeniffer Nasike Atetwe, BSc (Actuarial Science), International Diploma in Insurance Management

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INTRODUCTION

The year 2024 witnessed unprecedented climate and weather disasters globally, emphasizing the urgent need for resilience and adaptation initiatives. In the United States alone, 27 disasters caused damages exceeding \$1 billion each, including hurricanes, tornado outbreaks, wildfires, heatwaves, and flooding events. Hurricane Helene, the costliest, resulted in 219 deaths and caused an estimated \$79.6 billion in damages. Beyond the U.S., Cyclone Chido claimed over 1,000 lives, a heatwave in Bangladesh affected more than 33 million people, and a drought in Colombia has had significant economic consequences (NOAA, 2024; CNN, 2024).

These events highlight the growing vulnerability of communities to climate-related risks and underscore the importance of proactive adaptation programs. Decision-makers are increasingly seeking tools that not only mitigate the effects of disasters but also optimize resource allocation.

This essay argues that integrating **artificial intelligence (AI) with actuarial techniques** provides a rigorous, scalable, and actionable framework to evaluate and enhance climate change resilience and adaptation programs worldwide. Through illustrative global case studies, quantitative methods, and predictive modelling, this paper demonstrates how such an approach can help communities prepare for and respond effectively to climate disasters.

This paper contributes by offering a practical evaluation framework that actuaries and policymakers can adapt across diverse climate-risk contexts.

BACKGROUND AND LITERATURE REVIEW

Governments and organizations have implemented numerous initiatives to enhance climate resilience. In the United States, Louisiana upgraded its building codes after Hurricane Katrina to reduce infrastructure vulnerability, while New York City introduced the *Be a Buddy* program to connect volunteers with vulnerable populations during extreme heat events (NYC Mayor's Office, 2018). Florida has experimented with hurricane-proof communities, such as Hunter's Point, which were designed to withstand major storms (CNN, 2024).

Outside the U.S., developing countries face unique challenges due to limited resources and infrastructure. Bangladesh, prone to heatwaves and flooding, has invested in early warning systems and community preparedness programs. Similarly, Colombia's drought mitigation initiatives aim to protect agricultural livelihoods and the broader economy.

A recurring challenge remains: **evaluating the effectiveness of resilience programs quantitatively**. Many initiatives rely on anecdotal evidence or post-event assessments, which limits their ability to inform decision-making for future interventions.

Recent literature highlights the potential of AI and actuarial methods in addressing this gap. Machine learning models, such as XGBoost, can analyze complex datasets to predict climate risks and optimize program selection. Actuarial techniques, including discounted cash flow (DCF) analysis using real option theory, allow evaluators to quantify potential benefits and costs of interventions under uncertainty, as documented in the broader climate risk and disaster economics literature. Combining these approaches creates a robust framework to design, implement, and assess resilience programs effectively.

METHODOLOGY / FRAMEWORK

To maximize the impact of adaptation initiatives, a structured framework integrating AI and actuarial techniques is proposed. This framework consists of three key stages: **risk identification, program selection, and quantitative evaluation**.

RISK IDENTIFICATION

The first stage involves identifying high-risk areas and populations. Historical climate and disaster data, such as flood, hurricane, or wildfire frequency and intensity, can be analyzed using predictive models like XGBoost. XGBoost is effective for handling complex, non-linear relationships and large datasets, making it suitable for climate risk assessment. Variables such as precipitation patterns, elevation, population density, and infrastructure resilience are incorporated into the model to produce **illustrative probabilistic risk maps**.

Note: For this essay, risk maps and outcomes are hypothetical and based on published literature and expert assessments.

PROGRAM SELECTION

Once risks are identified, programs are prioritized based on expected impact and cost-effectiveness. Machine learning models can rank interventions by predicting their potential to reduce casualties, infrastructure damage, or economic losses. Social adaptation programs, such as community engagement or volunteer coordination, can be evaluated using **participant/non-participant methods**, comparing outcomes between neighborhoods involved and not involved in programs.

QUANTITATIVE EVALUATION

The final stage applies actuarial techniques to evaluate program outcomes. The **pre/post method** assesses changes in key indicators (e.g., fatalities, economic losses) before and after program implementation. For infrastructure-focused initiatives, **DCF analysis using real option theory** estimates the present value of avoided damages, incorporating uncertainty in climate projections and economic variables. This allows decision-makers to understand the expected return on investment (ROI) for each intervention and make informed choices about resource allocation.

Table 1
FRAMEWORK FOR AI AND ACTUARIAL EVALUATION OF ADAPTATION PROGRAMS (ILLUSTRATIVE)

Stage	Technique	Data Source	Expected Output
Risk Identification	XGBoost	Historical climate & population data	High-risk zones
Program Selection	ML prioritization	Socioeconomic & infrastructure data	Ranked interventions
Quantitative Evaluation	Pre/post & DCF	Program & financial data	ROI, risk reduction

This integrated framework allows programs to be **data-driven, scalable, and adaptable** to different geographies and types of disasters.

CASE STUDY: ILLUSTRATIVE FLOOD MITIGATION IN DHAKA, BANGLADESH

Problem Context

Dhaka, the capital of Bangladesh, faces frequent urban flooding affecting millions of residents and critical infrastructure. Traditional flood management strategies have often been reactive, resulting in high human and economic costs. To illustrate the potential application of AI and actuarial methods, a hypothetical pilot program is considered that combines predictive modelling with community-based adaptation measures.

Program Design (Illustrative)

The program includes:

- **Predictive Flood Mapping:** Using XGBoost to analyze rainfall, drainage patterns, population density, and topography.
- **Community Preparedness:** Training volunteers, establishing emergency shelters, and communicating evacuation plans.
- **Infrastructure Interventions:** Building embankments and upgrading drainage systems.

Quantitative Evaluation (Illustrative)

Evaluation employs three techniques:

- **Pre/Post Method:** Comparing flood-related damages and casualties before and after program implementation.
- **Participant/Non-Participant Method:** Measuring differences in preparedness outcomes between neighborhoods involved in the program and those not involved.
- **DCF Analysis Using Real Option Theory:** Estimating economic benefits of infrastructure improvements under uncertain climate projections.

Illustrative Findings

The following findings represent expected outcomes under the assumption that the proposed AI–actuarial framework is implemented using Dhaka-specific climate, demographic, and infrastructure data. The results are illustrative and informed by performance ranges reported in comparable urban flood risk studies in South and Southeast Asia and similar flood-prone urban environments, rather than derived from observed program data in Dhaka.

- **Predictive Accuracy:**
Under the assumed application of XGBoost to Dhaka flood data, the model is expected to identify flood-prone areas with approximately **85% classification accuracy**, consistent with accuracy ranges reported in urban flood susceptibility literature.
- **Social Impact:**
Assuming effective implementation of community preparedness initiatives in high-risk Dhaka neighborhoods, potential flood-related casualties are expected to decrease by approximately **20%** in participating areas relative to non-participating areas.
- **Economic Benefits:**
Applying actuarial discounted cash flow (DCF) analysis with real option considerations, the illustrative program yields an estimated **return on investment of \$1.5 for every \$1 invested over five years**, reflecting avoided damages and reduced emergency response costs.

Lessons Learned

The case study illustrates that combining AI, actuarial techniques, and community engagement can significantly enhance resilience outcomes. Key takeaways include:

- Predictive modelling enables targeted interventions in resource-limited settings.
- Actuarial evaluation quantifies social and economic impacts to support decision-making.
- Community involvement is critical for program success, especially in dense urban environments.

DISCUSSION AND IMPLICATIONS

Integrating AI and actuarial techniques offers several advantages for climate resilience programs:

- **Proactive Decision-Making:** Predictive models allow governments and organizations to anticipate disasters and allocate resources efficiently.
- **Cost-Effectiveness:** Quantitative evaluation identifies programs with the highest ROI, ensuring limited resources achieve maximum impact.
- **Scalability:** The framework can be applied to multiple disasters (hurricanes, wildfires, droughts) and across different countries.
- **Actuarial Role Expansion:** Actuaries can evaluate social and environmental interventions beyond traditional insurance contexts.

Challenges remain, including **data availability**, especially in developing countries, the need for **interdisciplinary collaboration**, and limitations in predictive accuracy for extreme events.

RECOMMENDATIONS FOR FUTURE RESEARCH

- **Integrating Multi-Source Data:** Combining climate, demographic, and socioeconomic datasets for robust predictive modelling.
- **Long-Term Impact Studies:** Evaluating sustained effects of social adaptation programs on vulnerable populations.

- **Hybrid Intervention Models:** Assessing combined infrastructure and behavioral programs for enhanced cost-effectiveness.
- **Open Data Sharing:** Encouraging governments, NGOs, and the private sector to share datasets to improve model accuracy and applicability.

Such research enables actuaries and policymakers to develop **adaptive, evidence-based programs** that enhance global resilience.

CONCLUSION

Climate-related disasters are increasingly frequent and costly, emphasizing the need for effective resilience and adaptation initiatives. This essay demonstrates that integrating **AI-driven predictive models with actuarial evaluation techniques** provides a **quantitative, scalable, and actionable framework** for assessing and optimizing climate adaptation programs.

The illustrative Dhaka case study highlights practical benefits: reduced casualties, measurable economic gains, and improved disaster preparedness. By leveraging predictive analytics, actuarial modelling, and community engagement, governments and organizations can make informed decisions, prioritize resources efficiently, and build resilience for the future.

Actuaries have a unique opportunity to contribute to climate adaptation by applying expertise in **quantitative evaluation, risk assessment, and resource optimization**, ensuring programs deliver tangible benefits worldwide.

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A Case for Climate Resilience

Brian Hinkle, FSA, MAAA

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Resilience and adaptation investments involve investing in tools now to mitigate loss in the future. This is a concept actuaries are very familiar with. In fact, resilience efforts are a lot like life insurance: you pay a smaller amount now so that if a bad day happens in the future, you'll be protected. People often feel that term life insurance can be a ripoff, because you may never get anything back. A common response to that thinking is that the consolation prize for never using your life insurance is that you lived! How do you quantify that benefit?

Similarly, most of us have health insurance, particularly for high-cost events like severe illness or injury. This does not stop us from going to the doctor to get an annual physical, vaccinations, or screenings. We understand that these actions, though they may feel unnecessary at the time, increase our resilience and help mitigate the bad day outcomes we hope to avoid. When faced with the question of whether you would rather have help rebuilding your house after a fire or never have your house burn down in the first place, I think we can all agree on the answer. Resilience is effective when the future loss is avoided, not when there's a payout associated with a future loss.

There's a common saying, "the best time to plant a tree is 20 years ago, the next best time is today." This applies to resilience investments as well, the best time to build a storm wall is 5 years before the last hurricane, the next best time is now, before the next one. This may all seem obvious to a risk management professional, but we don't get to make decisions in a vacuum. Resilience investments compete with other civic priorities for limited resources. They provide no immediate obvious benefit, material upfront costs, and therefore, often have limited support.

So, how can we help quantify the benefits of resilience investments and communicate them to the public in a way that resonates? Here are three ways: real world examples, stress testing, and insurance equivalents.

REAL WORLD EXAMPLES

Stories are the brain's natural language. Concepts become embedded in our minds through stories. On January 31, 1953, the devastating North Sea Flood struck the Netherlands. The nation's series of dikes failed, with almost 500 breaches, and the resulting flooding was devastating. 1,836 people drowned, 182,000 livestock animals died, and over 46,000 buildings were destroyed or damaged. Estimated property damage costs in today's value exceeded 2 billion euros. Sea surge flooding had been a consistent problem haunting the Netherlands for thousands of years. The 1953 flood was the final catalyst where the public will and the technology aligned to address the problem.

Over the ensuing decades, the Netherlands embarked on an ambitious project, the Delta Works, to address the problem. The cornerstone project was a 400 million euro movable storm surge barrier, called Maeslantkering and completed in 1997, that would protect inland regions while preserving historic sites and towns. The barrier automatically deploys when storm surge is projected above a certain threshold. In the 25+ years the barrier has been in operation, it has only automatically closed one time. But the Dutch people know that it is there and ready to protect them when the inevitable “big one” hits again. This provides peace of mind for economic and community flourishing in a way that the region has never known. The story and memory of the 1953 flood continued to motivate the Dutch people to invest in resilience for over 40 years.

STRESS TESTING

We’ll use the Netherlands example throughout the rest of the paper to illustrate the other methods as well. Stress testing is a great way to demonstrate the impact of resilience investments. The Netherlands has storm surge data dating back to the 1700s, with less consistent records dating back a thousand years prior to that as well. This wealth of data can be used in projecting frequency of storm surge events in the future. Major disasters like the 1953 flood, along with numerous smaller events can be studied to estimate severity of each event (absent a flood barrier). These frequency and severity estimates can provide a baseline estimate of annual storm surge costs.

The Maeslantkering sea barrier can handle storm surges up to five meters. The 1953 flood was the only storm surge event in modern history above five meters, at 5.4. This could lead us to estimate that the barrier can reasonably be expected to protect against all storm surge events in its useful operational lifetime. Summing up annual costs over this period, we can develop an estimate of the economic value of creating the barrier.

Climate change, and the resulting sea level rise, is increasing the frequency and severity of storm surge events. Actuaries can use climate scenarios from the Network for Greening the Financial System (NGFS) or other bodies to estimate the increased frequency and severity of these severe events, including events above five meters. These estimations can show both the increasing value the resiliency investment generates from mitigating more events, and the potential new exposure from more severe events that the wall cannot fully mitigate.

INSURANCE EQUIVALENTS

Finally, we can use the calculations in our scenario analysis to translate the impacts to a cost of insurance (COI) impact. A storm surge event would impact several different insurable assets including, homes, buildings, vehicles, ships, and lives. For simplicity’s sake, we’ll do the analysis on homes only. There are approximately 8 million homes in the Netherlands, with 60% of people living below sea level. So, let’s assume that means that 4.8 million homes ($8m * 60\%$) are vulnerable to sea level rise. For simplicity, we’ll assume average annual premium is 1,000 euros. The total annual premium for exposed houses would be 4.8 billion euros. We’ll assume that the annual expected storm surge cost is 40 million euros (one 1 billion euro event every 25 years). Assuming no profit margin, accounting for variability, or other considerations, this implies that needing to cover the risk of storm surge would increase insurance premiums by approximately 8.3 euros a year. If we assume full mitigation and a 50-year useful life for a sea wall, the average cost per household would be 1.7 euros per year. The cost of not investing in resilience is five times more expensive than building the wall, not to mention the amount of lives saved and improved quality of life. These are mostly made-up numbers, but a similar analysis could be done with real data. Tying the impact to a value that the public understands, the cost of their homeowner’s insurance for example, could help create buy-in for large upfront investments.

CONCLUSION

Resilience and adaptation investments are, at their core, practical tools for safeguarding communities against uncertain but potentially devastating future events. As the Netherlands' experience illustrates, the value of these investments is not measured by how often protective systems are triggered, but by the confidence and security they provide every day they stand ready. Through real-world examples, stress-testing analysis, and insurance-equivalent framing, we can translate complex risk-mitigation concepts into terms that resonate with both policymakers and the public.

Ultimately, the question is not whether resilience investments will eliminate all future loss. They will not. The question is whether the costs of preparedness today are justified by the avoided costs and preserved lives of tomorrow. When framed in this way, the answer becomes clear: resilience is not only a prudent financial strategy, but a societal imperative. By helping people understand these benefits in relatable, quantifiable terms, actuaries and risk professionals can play a critical role in building informed support for long-term investments that protect communities, strengthen economies, and enhance quality of life for generations to come.


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Improving Resilience of Post-Harvest Losses through Parametric Insurance

Saliya Jinadasa, AIAA and Yong XianTan

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INTRODUCTION

Much attention is given to crop losses during cultivation and harvest but little to post-harvest losses. This article explores a possible parametric insurance solution to cover post-harvest losses during storage due to weather related causes, which are becoming prominent with climate change. The ultimate objective of offering such parametric insurance is to mitigate the risk of post-harvest losses at the storage stage leading to reduced food wastage, improved food security, and food supply chain stability.

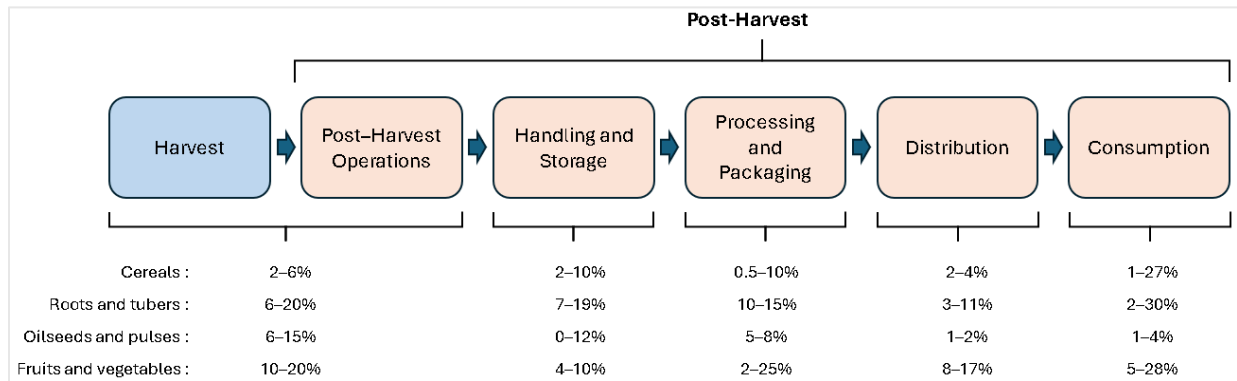
Typically, post-harvest losses occur during handling, storage, processing (e.g., packaging), distribution, sales, or at households. Post-harvest crop losses are a perennial and costly challenge for farmers and the food industry. A significant part of post-harvest losses occurs at the storage stage. Excess rainfall, high humidity, poor ventilation, pests, diseases, and contamination can cause crop degradation/spoilage at the storage stage leading to economic losses for farmers and reduce the food supply threatening food security for the society at large.

Post-Harvest Losses in Numbers

- The Food and Agriculture Organization (FAO) estimates that approximately 13% of all food produced globally is lost post-harvest [1].
- In developing nations, losses at storage and handling stages alone account for 7–10% of cereals and up to 19% of perishable crops [2].
- Small scale farmers are especially exposed due to limited access to modern storage infrastructure. For example, China reports grain losses of 7–13% at rural household storage facilities, compared with losses below 1% at the national reserve level [3].

The following diagram illustrates post-harvest losses at different stages from harvest to consumption. Percentages represent the proportion of losses of what enters each stage for different crop types.

Figure 1
LOSSES AT DIFFERENT STAGES FROM HARVEST TO CONSUMPTION



Based on data from [1] [2]

Traditional indemnity-based insurance products rarely address the risk of post-harvest losses particularly at the storage stage as claims assessment for spoilage can be slow, subjective, and costly particularly for small scale farmers. However, parametric insurance offers an efficient and cost-effective alternative as explored in this article to achieve the ultimate objective of risk mitigation of post-harvest losses at the storage stage by the following means.

- Financial security provided by coverage can help farmers to continue their livelihoods.
- Financial security can also help to invest in better infrastructure for storage facilities.
- As part of product support, provide training and awareness to farmers about best practices for storage facilities.
- Encourage farmers to adopt modern affordable technologies and practices which can lead to improved storage conditions.

CURRENT MARKET LANDSCAPE FOR POST-HARVEST LOSSES

Currently, only a handful of well-known schemes are available in the market for post-harvest loss protection. Pradhan Mantri Fasal Bima Yojana (PMFBY) [4] in India is a government scheme covering post-harvest losses, sowing failures, and other disasters. It provides coverage for up to two weeks post-harvest for crops that require drying in a cut-and-spread condition in the field, against hailstorms, cyclones, cyclonic rains, and unseasonal rains. The scheme has a parametric element to ensure timely payout of weather-induced losses.

PARAMETRIC PRODUCT DESIGN

Parametric insurance solutions are emerging as a pragmatic alternative to traditional insurance for several reasons:

- Highly customizable to specific coverage needs.
- Allow faster and simpler claim payments. Payouts can be made within a short timeframe after a weather event triggering a pre-determined threshold.
- Triggers can be based on third-party verifiable weather data improving transparency.
- Provide cost efficiency by eliminating costly spoilage inspections particularly in disperse rural areas.
- Provide scalability with the possibility to roll out to large farmer networks or cooperatives.

- Potential to compensate for quality degradation such as crop downgrading even when total losses do not occur.
- Emergence of specialized parametric service providers in recent years provides more options in terms of service providers.

However, there are some limitations:

- Unlike traditional indemnity-based insurance, there can be exposure to basis risk¹ where spoilage occurs despite trigger thresholds not being met.
- Farmers may lose trust in the system if spoilage occurs, but trigger thresholds are not met.

COVERAGE AND TARGET SEGMENTS

The coverage objective is to protect the loss of value of harvest at the storage stage against degradation/spoilage from adverse weather conditions such as high humidity and excessive rainfall. This generic solution can be adopted for a specific crop type.

Target user segments can include individual farmers with on-farm storage facilities such as granaries and cold rooms, farmer cooperatives with shared storage facilities, and agribusiness aggregators purchasing directly from farmers.

TRIGGER INDEX

A trigger should be relatively easy to measure, verifiable, transparent, and strongly correlated with degradation/spoilage to reduce basis risk. Possible indices include:

- **Daily Average Relative Humidity²** that can be measured at weather stations closer to farms or via satellite-derived atmospheric moisture data. Alternatively, low-cost measurement tools such as Hygrometers can be installed at farm storage facilities to monitor and report relative humidity levels.
- Relative humidity meeting an agreed value over a specified period can be considered for the trigger (e.g., a daily average over 85% for five consecutive days).
- **Cumulative Rainfall** over an agreed period. (e.g., 100 mm cumulative rain over five consecutive days).

In fact, to address basis risk, a two-factor index that includes both relative humidity and cumulative rainfall can be considered.

Trigger index thresholds can be tailored to a target region and its crops, based on their specific spoilage patterns. Moreover, different threshold options can be considered for different storage types (e.g., climate-controlled vs. traditional).

¹ The difference between pay-out from parametric insurance and underlying loss. For more detail see <https://www.interactivebrokers.com/campus/glossary-terms/basis-risk/>

² *Relative Humidity*, ScienceDirect Topics, Elsevier, accessed February 13, 2026, <https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/relative-humidity>

CONSIDERATIONS FOR UNDERWRITING

The following are a few preconditions for consideration to be eligible for coverage.

- A minimum acceptable level of storage facilities to mitigate the risk of losses conforming to the ultimate objective of waste reduction and food security improvement.
- For example, consider low-cost evaporative cooling arrangements as a precondition for small scale farmers.
- Another example is to consider the use of hermetic storage bags instead of traditional jute bags as a precondition. Hermetic bags reduce spoilage risk during storage [5].
- Reporting of yield within a given timeframe post-harvest to determine the market value of harvest.
- However, as an alternative historical yield data can be considered particularly for crops that require only a short storage period. For example, consider the average yield for past seven years excluding two years of declared disasters.

Accumulation risk is likely to be a concern. Limiting the coverage to a specific area, and the selection of triggers and payout structures can help to manage accumulation risk in a more predictable manner.

The duration of coverage depends on the type of crops being protected. Perishable harvest such as fruits and vegetables can have a short coverage period whereas the coverage for grains can be longer.

PAYOUT STRUCTURE

The payout structure specifies how claims are settled in case the parametric cover is triggered. If a two-factor index is adopted, a possible payout structure can look like the following aligning payouts with likely severity of spoilage and loss in market value.

Table 1
A SAMPLE PAYOUT STRUCTURE

Two-Factor Index	Payout as a Percentage of Market Value of Harvest
RH \geq 85% and $<$ 90% cumulative rainfall \geq 100mm and $<$ 150mm for five consecutive days	30%
RH \geq 90% and $<$ 95% and cumulative rainfall \geq 150mm and $<$ 200mm for five consecutive days	60%
RH $>$ 95% and cumulative rainfall $>$ 200mm for five consecutive days	100%

For example, if daily average relative humidity is between 85% and 90% and cumulative rainfall is between 100mm and 150mm for five consecutive days, based on the payout structure, the insured can claim 30% of the market value of the harvest.

PRICING

Typically, the pricing of parametric insurance is mainly driven by the probability of occurrence of a trigger event. Historical rainfall and relative humidity data spanning over a sizeable period are likely to be readily available from credible third-party sources gathering such information. Moreover, compared to a

traditional indemnity-based coverage, a simple index-based trigger can make pricing more competitive, particularly when affordability is a key concern for small scale farmers.

DISTRIBUTION

Based on target segments, parametric insurance has the scalability to reach out to a large section of the farmer community through different distribution channels. The following are several for consideration:

- Policies can be sold through cooperatives and agribusiness aggregators and financed through cooperatives or other funds.
- For small scale farmers, policies can be bundled with microfinance or other loans taken for their post-harvest needs.
- As part of food security initiatives, Governments and development agencies can distribute parametric coverages and subsidize premiums particularly for small scale farmers.
- Digital channels: with the ubiquitous prevalence of mobile phones, mobile apps and SMS platforms can be used for policy issuance, trigger notifications, and payout alerts.
- If farmers are already on a parametric or other scheme for the protection of their harvest, post-harvest protection can be offered as an add-on coverage.

CONCLUSION

Post-harvest crop losses are a perennial and costly challenge threatening livelihood of farmers and food security for the society at large. Post-harvest losses can occur at different stages of the food supply chain and losses at the storage stage can be significant. Traditional indemnity-based insurance products rarely address the risk of post-harvest losses particularly at the storage stage. Flexibility, transparency, simple and faster claim settlement, cost efficiency, and scalability associated with parametric insurance make it ideal to address losses from degradation/spoilage at the storage stage due to weather related causes such as high humidity and excessive rainfall. Such parametric insurance solutions not only protect livelihood of farmers but also can contribute to food security, waste reduction, and food supply chain stability.

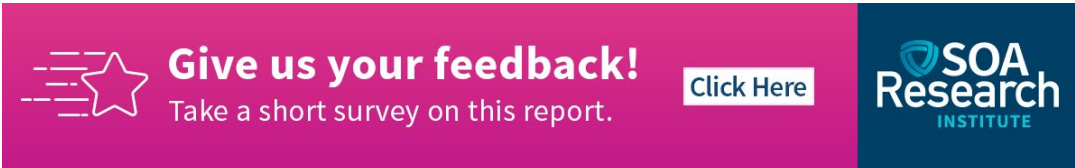
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Beyond the Threshold: An Actuarial Perspective on Evaluating Climate Adaptation in an Age of Escalating Disasters

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INTRODUCTION: ACTUARIAL RESPONSIBILITY IN AN UNSTABLE CLIMATE REGIME

Actuarial science has traditionally relied on historical experience, stable probability distributions, and the assumption that past outcomes provide a reliable guide to future risk. Climate change fundamentally challenges these assumptions. The surge in climate-related disasters during 2024 and 2025, marked by an unprecedented number of billion-dollar loss events, signals a transition toward a highly volatile and compounding risk environment. Extreme weather events are no longer rare or isolated; they are increasingly frequent, overlapping, and geographically widespread.

This shift creates a critical responsibility for the actuarial profession. While improving catastrophe models and refining risk pricing remain essential, actuaries must also contribute to the systematic evaluation of interventions designed to reduce climate-related losses. Governments, insurers, and communities are investing heavily in climate resilience and adaptation (CRA) initiatives, yet decision-makers often lack rigorous frameworks to assess their effectiveness, cost efficiency, and social impact. This paper argues that actuaries are uniquely positioned to fill this gap.

By integrating forward-looking climate risk, causal evaluation methods, strategic valuation techniques, and equity considerations, actuaries can support evidence-based decisions that strengthen long-term resilience rather than merely reallocating risk.

CLASSIFYING CLIMATE RESILIENCE AND ADAPTATION INITIATIVES

Effective evaluation begins with recognizing that climate adaptation strategies differ in purpose, structure, and impact pathways. Treating all resilience initiatives uniformly risks misinterpretation of their outcomes. This paper adopts a two-dimensional classification to guide actuarial assessment.

PHYSICAL VS. SOCIAL-INSTITUTIONAL INTERVENTIONS

Physical or engineering-based interventions focus on reducing damage by strengthening the built environment. Examples include enhanced building codes, flood barriers, elevated infrastructure, and wind-resistant construction. Their benefits are typically observed through reduced asset damage, lower repair costs, and improved structural performance during extreme events.

Social and institutional interventions, by contrast, enhance the capacity of individuals and communities to prepare for, respond to, and recover from climate stress. These include early warning systems, public

health initiatives, insurance mechanisms, and community-based support programs. Their benefits often appear indirectly, through reduced mortality, faster recovery, and lower secondary economic losses.

SHOCK-FOCUSED VS. STRESS-FOCUSED ADAPTATION

Some initiatives are designed to address sudden, high-impact events such as hurricanes or floods. These shock-focused strategies aim to prevent catastrophic failure during extreme episodes. Other initiatives target gradual and persistent pressures such as rising temperatures, sea-level rise, or prolonged drought. These stress-focused strategies support long-term adjustment rather than immediate protection.

Positioning a CRA initiative within this typology is essential, as it determines appropriate metrics, modeling approaches, and evaluation horizons.

QUANTITATIVE EVALUATION BEYOND TRADITIONAL DISCOUNTING

Discounted cash flow analysis remains a foundational tool in actuarial evaluation, but it is often insufficient when applied to climate adaptation. CRA investments involve long time horizons, uncertain hazard trajectories, and irreversible commitments, all of which limit the usefulness of static valuation methods.

Causal Methods for Measuring Effectiveness

To evaluate whether an adaptation initiative truly reduces risk, actuaries must distinguish causation from correlation. Simple before-and-after comparisons may be distorted by changing exposure, economic conditions, or climate trends. More robust quasi-experimental techniques, such as difference-in-differences analysis or matched comparison groups, enable actuaries to isolate the incremental effect of an intervention.

For example, insurance claims from retrofitted properties can be compared with statistically similar non-retrofitted properties to estimate the loss reduction attributable to adaptation measures.

Predictive Analytics and Risk Targeting

Machine learning methods offer powerful tools for identifying vulnerable assets and populations. By combining climate variables, infrastructure characteristics, and socioeconomic indicators, predictive models can highlight areas most likely to experience severe losses. While these techniques may not always provide causal explanations, they are valuable for prioritizing adaptation investments and improving program efficiency.

Strategic Valuation Using Real Options Analysis

Many adaptation projects allow for staged implementation, learning over time, or adjustment as new information emerges. Real options analysis captures this flexibility by treating adaptation investments as strategic choices rather than fixed commitments. Phased infrastructure upgrades or pilot programs may appear costly under conventional valuation but become economically attractive once the value of flexibility and learning is incorporated.

EQUITY AND BEHAVIORAL DIMENSIONS OF ADAPTATION

A purely financial assessment provides an incomplete picture of adaptation effectiveness. CRA initiatives can unintentionally reinforce social inequalities if benefits accrue primarily to affluent communities while vulnerable populations remain exposed.

Actuarial evaluation should therefore include an explicit equity assessment. Issues of affordability, access, and potential risk displacement must be examined. Programs designed to protect high-risk populations, such as elderly individuals during extreme heat events, demonstrate that social benefits can be both measurable and actuarially significant.

Behavioral factors also influence program success. Even technically effective measures may fail if adoption rates are low due to present bias, perceived inconvenience, or mistrust. Incorporating behavioral assumptions into participation and compliance models improves the realism of projected benefits and can inform more effective program design.

ILLUSTRATIVE CASE STUDIES

Strengthened Building Codes in Louisiana

Following major hurricane losses, Louisiana implemented stricter construction standards to improve wind and flood resistance. Actuarial evaluation balances higher upfront construction costs against long-term reductions in expected losses. Empirical claims data and catastrophe modeling provide evidence that enhanced codes significantly reduce tail risk, benefiting insurers, homeowners, and public finances.

Community-Based Heat Resilience in New York City

New York City's *Be a Buddy* program demonstrates the value of social resilience. By connecting volunteers with vulnerable residents during extreme heat events, the program reduces mortality and emergency healthcare usage. From an actuarial perspective, these outcomes translate into measurable economic and social value, even though benefits extend beyond traditional insurance metrics.

Hurricane-Resilient Communities in Florida

Hurricane-resilient communities in Florida provide opportunities for post-event validation. Comparing actual damage outcomes with those from conventional developments reveals substantial reductions in repair costs and downtime. These results support the case that resilience investments can stabilize insurance markets and enhance long-term property value.

AN INTEGRATED ACTUARIAL FRAMEWORK FOR DECISION-MAKING

A structured approach to evaluating CRA initiatives can be summarized in five steps:

- Classification: Identify the type and objective of the intervention.
- Metric Selection: Define appropriate financial, social, and risk-based indicators.
- Advanced Valuation: Incorporate uncertainty, flexibility, and behavioral response.
- Equity Assessment: Evaluate distributional impacts and systemic effects.
- Communication: Present findings clearly to support informed decision-making.

For the actuarial profession, this implies expanding traditional practice boundaries to include climate-informed data standards, transparent evaluation methods, and innovative resilience-linked financial instruments.

GOVERNANCE, DATA, AND COMMUNICATION CHALLENGES

The climate-driven disasters of 2024 and 2025 represent a structural shift in the global risk landscape. In this environment, actuarial value extends beyond pricing increasingly volatile risks to guiding investments that reduce losses before they occur. Evaluating climate adaptation initiatives requires integrating advanced analytics, strategic thinking, equity considerations, and behavioral insight.

By adopting a broader and forward-looking perspective, actuaries can help reposition resilience as a value-generating investment rather than a discretionary cost. In doing so, the profession can play a central role in shaping a more stable, equitable, and adaptive future under climate uncertainty.

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