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ORIGINAL ARTICLE

ECOLOGICAL DEFICITS AS DRIVERS OF INSURANCE DEPENDENCE: THE COMPENSATORY ROLE OF THE INSURANCE SECTOR IN G7 ECONOMIES

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Abstract
This study investigates the interplay between natural disaster frequency, economic factors, environmental sustainability, and the insurance sector in G7 countries from 1989 to 2022. Employing the two-step System Generalised Method of Moments (System GMM) approach to account for endogeneity and persistence, this study examines how climate-induced disaster frequency, economic growth, greenhouse gas emissions, climatic variables, and the Load Capacity Factor (LCF), which serves as a comprehensive measure of environmental sustainability, affect insurance market penetration. Our empirical findings validate the Compensatory Hypothesis proposed in this study by demonstrating a significant negative relationship between LCF and insurance penetration. This implies that as ecological deficits widen and natural buffers are lost, G7 economies increasingly rely on the insurance sector as a financial substitute to manage disaster-related shocks. While economic growth and disaster frequency act as traditional demand drivers, the erosion of environmental sustainability emerges as a structural determinant forcing a defensive expansion of the insurance market. By foregrounding LCF, this study offers an alternative macro-financial perspective on how environmental limits interact with financial risk transfer systems. The results emphasize that financial resilience cannot be decoupled from ecological sustainability, providing actionable insights for policymakers to integrate nature-based solutions into disaster risk reduction strategies.

Keywords
Insurance Penetration, Load Capacity Factor, System GMM, Systemic Risk, Natural Disasters, Compensatory Hypothesis, Environmental Policy, G7 Economies.

JEL Classification
G22, Q54, C23, Q56.

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1. INTRODUCTION

The escalating frequency of climate-induced catastrophes has shifted environmental degradation from a theoretical concern to a tangible systemic risk for global financial markets (World Economic Forum [WEF], 2023). As the physical impacts of climate change intensify, the global insurance sector has increasingly assumed the role of a primary financial shock absorber, tasked with mitigating economic losses and facilitating recovery (Von Peter et al., 2024). In developed economies, particularly the G7, high insurance penetration, defined as the ratio of total premiums to GDP, is conventionally interpreted as a metric of financial resilience and adaptive capacity (OECD, 2020). However, this conventional interpretation presents a critical paradox: Does a rising insurance penetration rate invariably signal a robust financial system, or can it also represent a defensive expenditure driven by the erosion of natural environmental buffers?

This distinction is not merely semantic but fundamental to understanding the sustainability of the insurance sector. While existing literature has extensively explored the demand-pull factors of insurance, such as economic growth (Apergis & Poufinas, 2020) and disaster frequency (Yörübulut, 2025), the supply-side constraints imposed by ecological limits remain under-investigated. Specifically, the relationship between the Load Capacity Factor (LCF) of a nation, which is a comprehensive measure of ecological sustainability combining biocapacity and ecological footprint, and its reliance on insurance markets has not been empirically established.

This study challenges the standard narrative by proposing a Compensatory Hypothesis. We posit that as the ecological deficit of a country widens (indicated by a declining LCF), the natural capacity of the environment to absorb shocks, such as wetlands absorbing floodwaters, diminishes. Consequently, economic agents are forced to substitute this free natural capital with costly financial capital in the form of insurance, thereby driving up penetration rates. In this framework, high insurance penetration in the absence of environmental sustainability is not solely a sign of market sophistication but a symptom of insurance dependence necessitated by ecological overshooting. This structural link between environmental degradation and insurance demand is conceptualised through the lens of natural capital substitution and defensive expenditures theory (Arrow et al., 2012; Jaszi, 1958). In traditional environmental economics, ecosystem services function as non-priced natural assets providing intrinsic, biophysical buffering mechanisms against shocks. When an economy operates under a persistent ecological deficit, this protective capacity is compromised, forcing economic agents to substitute lost ecological regulations with commercial financial capital. Therefore, a rising insurance penetration in the presence of ecological overshooting is modeled as a mandatory structural defensive expenditure aimed at financial risk transfer.

The G7 countries (Canada, France, Germany, Italy, Japan, the United Kingdom, and the United States) provide an ideal laboratory for testing this hypothesis. These nations hold the dual distinction of possessing the world's most advanced insurance markets while simultaneously exhibiting significant ecological footprints (Global Footprint Network, 2023). Furthermore, the heterogeneity in their disaster exposure and insurance market structures, ranging from the state-subsidized flood programs in the US to the private-market dominance in the UK, requires a nuanced analysis.

To unravel these complex dynamics, this study analyses panel data from G7 countries over the period 1989–2022. Methodologically, the two-step System Generalised Method of Moments (System GMM) approach is employed. This dynamic estimator is uniquely suited to the specified research question for two reasons: first, it accounts for the persistence of insurance behaviors where past coverage influences current demand; and second, it rigorously addresses the potential endogeneity between economic growth, disaster occurrence, and insurance penetration, a common pitfall in static models (Arellano & Bover, 1995).

While the System GMM estimator is a well-established methodological tool, the primary contribution of this study is fundamentally content-related and theoretical. An alternative macroeconomic risk mechanism is introduced by directly linking the Load Capacity Factor (LCF) to insurance market dynamics. Specifically, it is argued that the depletion of natural capital such as the loss of wetlands or deforestation diminishes the environment's innate shock-absorption capacity. From an actuarial perspective, this physical degradation systematically amplifies tail risks and inflates technical risk premiums. Consequently, economic agents are forced into a regime of defensive consumption, substituting lost, free ecological services with costly financial contracts. By integrating LCF into the demand function, this study contributes to the empirical literature by documenting that rising insurance penetration in G7 economies is not solely a function of market sophistication or wealth accumulation, but a structural, compensatory response to ecological deficits.

The remainder of this paper is organised as follows: Section 2 critically reviews the literature on the nexus between environmental quality and insurance; Section 3 details the data and the System GMM methodology; Section 4 presents the empirical findings; and Section 5 discusses the policy implications of the compensatory role of insurance in the face of ecological limits.

2. LITERATURE REVIEW

The interplay between the insurance sector, economic development, and environmental sustainability has evolved from a niche topic into a central theme in financial economics. While early literature primarily focused on the financial determinants of insurance demand, known as the insurance-growth nexus, recent scholarship has expanded to include climatic and ecological dimensions. A critical evaluation of the existing literature reveals three distinct theoretical strands: the macroeconomic and catastrophe-driven demand, the impact of climatic volatility on insurability, and the emerging debate on ecological limits.

A well-established strand of literature posits a symbiotic relationship between economic growth and insurance market development. Studies by Apergis and Poufinas (2020) and Ding and Li (2025) argue that economic growth fosters insurance penetration by increasing disposable income and the value of insurable assets. This demand-pull theory suggests that as G7 economies expand, the capacity to afford premiums increases, a relationship that necessitates controlling for GDP per capita in empirical models. However, wealth alone does not explain the variance in penetration. The risk-response hypothesis suggests that the frequency of natural disasters acts as a catalyst for insurance uptake. Von Peter et al. (2024) and Yörübulut (2025) demonstrate that disaster events heighten risk perception, driving both households and firms to seek financial cover. Yet, there is a divergence in the literature regarding the sustainability of this mechanism. While Chang and Berdiev (2013) suggest that disasters stimulate market development, others warn of a potential protection gap where extreme frequency leads to insurers exiting high-risk zones, a nuance that necessitates the use of dynamic models to capture the persistence of insurance demand.

Beyond event frequency, the physical drivers of climate change, specifically temperature and precipitation anomalies, have come under scrutiny regarding their impact on insurability. Tucker (1997) was among the first to identify that rising global temperatures directly correlate with increased claim severity, particularly in property and casualty lines. Recent studies by Giuzio et al. (2024) corroborate this, linking thermal stress to broader systemic financial risks. However, the literature presents conflicting evidence regarding precipitation. While extreme rainfall causes flooding and increases claims, erratic precipitation patterns complicate actuarial pricing models. Cooper et al. (2008) and Le Quesne et al. (2017) highlight that unlike temperature, which has a relatively linear risk trajectory, precipitation variability can lead to model uncertainty, potentially suppressing supply rather than simply increasing demand. This theoretical ambiguity highlights the need to analyse temperature and precipitation as distinct vectors within the empirical framework.

The most contentious debate in recent literature, however, concerns the bidirectional relationship between environmental quality and insurance. One perspective, supported by Rizwanullah et al. (2022) and Joof et al. (2023), argues that insurance markets promote environmental quality by facilitating investments in renewable energy, often referred to as the green investment hypothesis. Conversely, Altarhouni et al. (2021) and Li et al. (2022) provide empirical evidence of a scale effect, where insurance expansion supports carbon-intensive industrial activities, thereby degrading environmental quality. A critical limitation of these studies is their reliance on Carbon Dioxide (CO_2) emissions as the sole proxy for environmental degradation. It is argued that while CO_2 is a flow variable representing pollution, it fails to capture the comprehensive carrying capacity of the environment. This gap is addressed by the Load Capacity Factor (LCF), utilized by Pata and Samour (2023), which compares biocapacity to the ecological footprint to offer a holistic measure of a nation's ecological solvency.

While Pata and Samour (2023) examined LCF in OECD countries, the specific mechanism by which ecological deficits influence insurance penetration remains underexplored in G7 nations.

Recent frontier research increasingly emphasizes the systemic financial vulnerabilities triggered by climate-induced ecological tipping points and nature loss (Mikaelsson, 2026; Gardes-Landolfini et al., 2024). Modern scholarship has begun to recognize that traditional financial hedges and insurance mechanisms face severe stress when underlying natural assets fail, potentially amplifying systemic risks (Jourde & Moreau, 2022). Furthermore, while the latest analytical frameworks have started to explore the dynamic impacts of macroeconomic factors on the Load Capacity Factor (Islam et al., 2024), these studies predominantly maintain a macro-financial or energy-focused perspective without decomposing the actuarial burden shifted specifically onto the insurance sector.

The existing literature largely treats environmental degradation as an outcome of economic activity. This study reverses the causality, positing a Compensatory Hypothesis. The central hypothesis dictates that as the LCF declines, signaling a loss of natural buffers, the insurance sector is forced to compensate for the lost ecological services, thereby driving up penetration rates as a defensive expenditure. By integrating LCF into a dynamic panel framework alongside disaster frequency and economic variables, this research bridges the gap between ecological economics and risk finance, offering an alternative structural explanation for the high insurance dependence observed in advanced economies.

3. DATA AND METHODOLOGY

3.1. Data Sourcing and Variable Characterization

This study analyses a balanced panel dataset of G7 countries (Canada, France, Germany, Italy, Japan, the United Kingdom, and the United States) spanning the period from 1989 to 2022. The selection of variables is grounded in the Compensatory Hypothesis, aiming to capture the functional relationship between ecological limits, disaster frequency, and financial risk transfer mechanisms.

The dependent variable is insurance penetration (INS), defined as the ratio of total gross written premiums to GDP. Sourced from the Swiss Re Institute's Sigma Database, INS serves as a proxy for the financial absorption capacity of the economy against external shocks, reflecting the extent to which risks are transferred from private and public balance sheets to the insurance sector. To measure environmental sustainability, the LCF is utilised, obtained from the Global Footprint Network. Unlike traditional emission metrics, LCF provides a comprehensive measure of ecological solvency by calculating the ratio of biocapacity to the ecological footprint. An LCF value below 1 indicates an ecological deficit, where resource consumption exceeds the regenerative capacity of the environment. This variable is pivotal for testing whether declining natural buffers drive the demand for financial compensation.

The frequency of natural disasters (NDIS) is sourced from the Emergency Events Database (EM-DAT), maintained by the Centre for Research on the Epidemiology of Disasters (CRED). This variable aggregates climatological, meteorological, hydrological, and geophysical events. While it is acknowledged that EM-DAT's entry thresholds might exclude smaller localized events, it remains the most robust standard for capturing major systemic shocks in G7 economies that influence reinsurance pricing cycles.

To isolate the specific effects of these variables, the model incorporates a set of control variables representing macroeconomic and climatic conditions. Real GDP per capita sourced from the World Bank is included to account for the income effect on insurance demand. Furthermore, climatic variations are captured through December average temperature and precipitation data from the World Bank Climate Data. The operationalisation of December monthly averages, rather than annual means, is strategically and institutionally grounded in the structural dynamics of global reinsurance markets. Within G7 economies, the vast majority of commercial property, casualty, and catastrophic reinsurance treaties undergo structural premium pricing, risk-modelling evaluations, and contract renewals during late December and early January (Aon, 2023). December climatic anomalies directly capture the immediate winter shocks (e.g., extreme freeze events, winter storms, and initial hydrological accumulations) that heavily dictate the technical loss-reserve formulations and premium volume adjustments recorded at the financial year-end. Hence, utilizing December metrics provides a synchronous reflection of the climate-finance nexus in institutional balance sheets. Lastly, per capita CO_2 emissions from the Carbon Dioxide Information Analysis Center (CDIAC) are included to control for anthropogenic environmental pressure. Detailed definitions, units, and data sources for all variables utilized in the analysis are provided in Table 1.

Table 1
Descriptions and Sources of the Data

Variable	Abbreviation	Definition	Unit	Source
Insurance Penetration (INS)	INS	Ratio of total insurance premiums to GDP	%	OECD Database, Swiss Re Sigma
Natural Disaster Frequency	NDIS	Number of natural disasters per year	Count	EM-DAT (CRED)
Economic Growth	GDP	Per capita (Constant 2015)	$	World Bank
Temperature	TEMP	December average air temperature	°C	World Bank Climate Data.
Greenhouse Gas Emissions	GHG	Per capita carbon dioxide emissions	MetricTons	CDIAC, Global Carbon Project
Precipitation	PREC	December average precipitation	mm	World Bank Climate Data.
Load Capacity Factor	LCF	Ratio of biocapacity to ecological footprint (both in global hectares per capita)	Index	Global Footprint Network

3.2. Descriptive Trends and Risk Landscape

Before proceeding to the econometric estimation, it is essential to contextualize the distribution of risks and market responses across the G7. Table 2 summarizes the cumulative frequency of disaster events and the associated economic and insured losses over the study period.

Table 2

Overview of Climate-Related Disasters and Associated Economic and Insured Losses in G7 Countries (1989–2022)

Disaster		Biological	Climatological	Geophysical	Hydrological	Meteorological	Total
Canada	Number	4	22	0	39	42	107
	Insured losses		4913747		4061175	4791581	13766503
	Total losses		18866667		16518469	15416414,	50801550
France	Number	1	11	2	57	90	161
	Insured losses				8570831	20716891	29287722
	Total losses		3967277		15686257	59157737	78811271
Germany	Number	1	0	2	19	68	90
	Insured losses			12905	18026043	24973574	43012522
	Total losses			127934	88034216	49300203	137462353
Italy	Number	1	13	19	46	33	112
	Insured losses			3930275	851180	406442	5187897
	Total losses		9882939	44422855	41596283	13465757	109367834
Japan	Number	1	1	43	43	137	225
	Insured losses			72182466	7660705	82473546	162316717
	Total losses			654557201	44668891	162135141	861361233
United Kingdom	Number	1	1	2	34	53	91
	Insured losses			44087	13799318	19339706	33183111
	Total losses			88173	34362840	26174772	60625785
United States	Number	4	116	22	171	574	887
	Insured losses		84827951	22336371	26118536	768236856	901519714
	Total losses		210376951	82293729	142326300	1563946640	1998943620

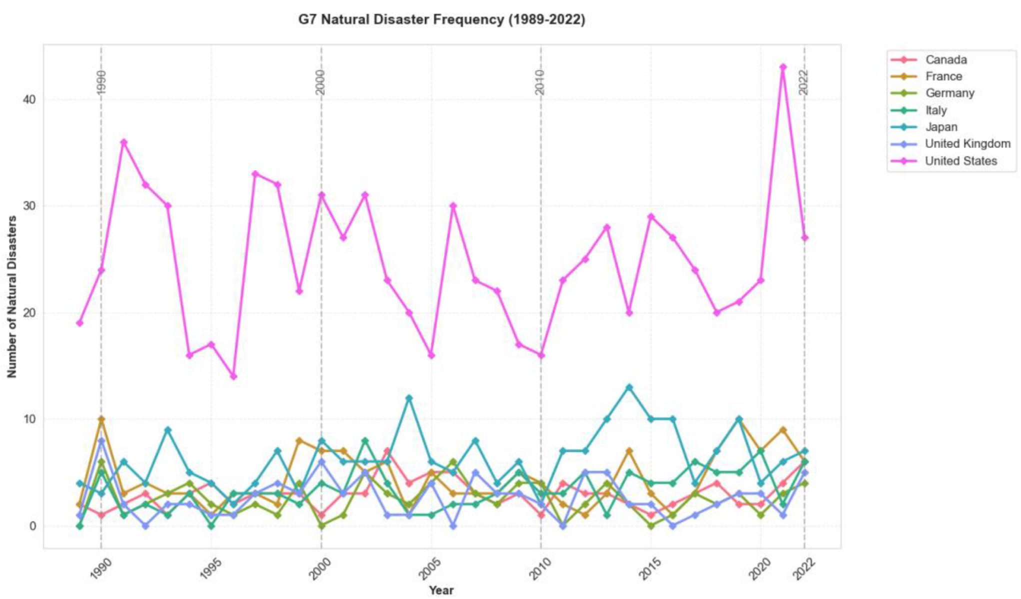
EM-DAT: Loss figures in (‘000 US) (2022 values)

As indicated in Table 2, there is significant heterogeneity in risk exposure and financial coverage. The United States recorded the highest activity with 887 disasters and total damages of approximately $1.99 trillion, of which a substantial portion ($901.5 billion) was insured. In stark contrast, Italy exhibits a concerning protection gap; despite suffering over $109 billion in total damages from 112 events, only about $5.19 billion was covered by insurance, resulting in a coverage ratio of less than 5%. This disparity underscores the structural differences in how G7 nations financially manage climate risks.

To visualize the temporal evolution of these risks, Figure 1 illustrates the trend of natural disaster frequency across the panel.

Figure 1

Natural Disasters Frequency in G7 Countries (1989-2022)



The graphical analysis in Figure 1 confirms that disaster risks are asymmetrically distributed. The United States consistently faces the highest frequency due to its vast geographical exposure to meteorological events, whereas countries like Japan face concentrated spikes driven by geophysical and hydrological events. Correspondingly, the response of the insurance market is depicted in Figure 2.

Figure 2

Insurance Penetration Rates in G7 Countries(1989-2022)

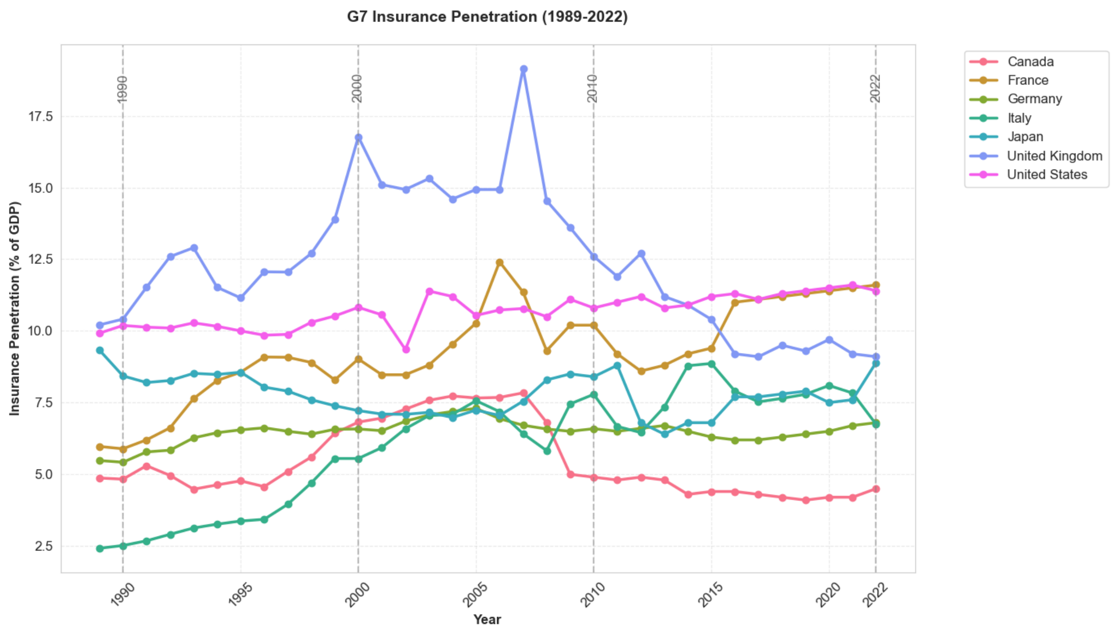
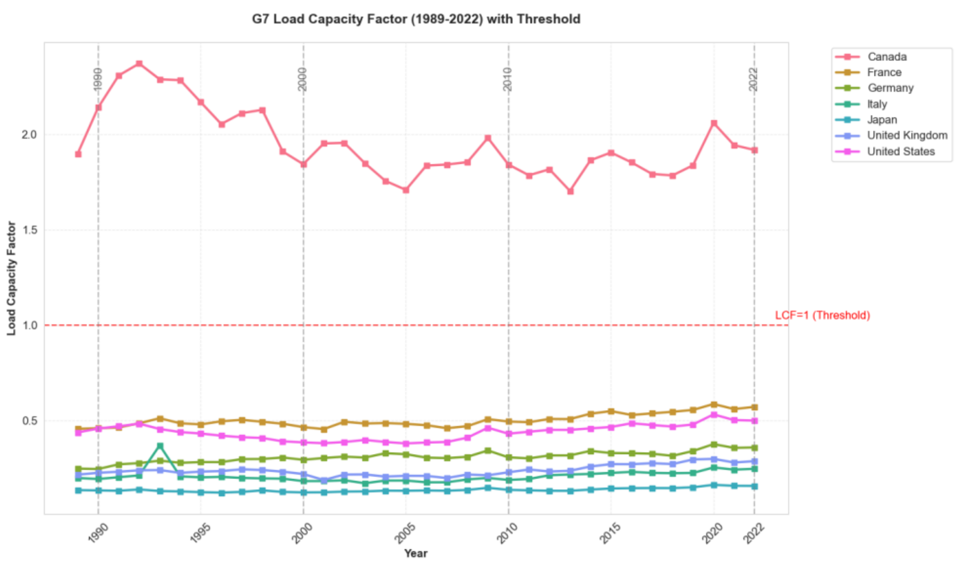


Figure 2 reveals that the United Kingdom and the United States maintain the highest insurance penetration rates, consistently exceeding 10%, which suggests a mature reliance on market-based risk transfer. Conversely, Germany, Italy, and Canada exhibit lower penetration rates (typically below 6%), indicating that despite high physical exposure to climate risks, these economies rely more heavily on other forms of recovery funding or face barriers to market deepening.

Crucially, to understand the structural drivers of this dependence, Figure 3 presents the trajectory of the LCF.

Figure 3

Load Capacity Factor in G7 Countries(1989-2022)



The trends in Figure 3 demonstrate that most G7 countries, particularly the US, UK, and Japan, operate under a persistent ecological deficit (low LCF). Even Canada, which historically possessed a surplus, shows a declining trajectory. This widespread erosion of ecological capital supports the study's premise that G7 nations are increasingly losing their natural buffers, potentially necessitating the compensatory expansion of insurance mechanisms analysed in the subsequent econometric section.

3.3. Econometric Strategy: System GMM

To empirically investigate the relationship between insurance penetration and the explanatory variables, grounded in the proposed Compensatory Hypothesis, the following dynamic panel data model is specified:

$$INS_{it} = \alpha_0 + \delta INS_{i,t-1} + \beta_1 NDIS_{it} + \beta_2 In(GDP_{it}) + \beta_3 TEMP_{it} + \beta_4 PREC_{it} + \beta_5 GHG_{it} + \beta_6 LCF_{it} + \mu_i + \gamma t + \epsilon_{it} \quad (1)$$

In Equation (1), the subscripts i $(i = 1, \dots, N)$ and t $(t = 1, \dots, T)$ denote the cross-sectional country unit and the time period, respectively. The dependent variable, INS_{it}, represents the level of the insurance penetration rate (measured as a percentage of GDP), while INS_{it-1} is the lagged dependent variable included to capture the dynamic persistence and structural hysteresis of the insurance market. Regarding the explanatory variables, $NDIS_{it}$ denotes the frequency of natural disasters, and $In(GDP_{it})$ is the natural logarithm of real GDP per capita. The model explicitly incorporates climatic and environmental determinants within a linear-logarithmic (semi-log) structural framework, where $TEMP_{it}$ and $PREC_{it}$ represent December average temperature and precipitation, respectively, and GHG_{it} denotes per capita greenhouse gas emissions. Crucially, LCF_{it} represents the LCF, which serves as our primary proxy for ecological sustainability. Finally, μ_i captures unobserved country-specific fixed effects, γt represents time-specific effects, and ϵ_{it} is the idiosyncratic error term.

Estimating Equation (1) using standard Ordinary Least Squares (OLS) or Fixed Effects (FE) techniques yields inconsistent and biased results. This is primarily because the lagged dependent variable $(INS_{i,t-1})$ is mathematically correlated with the country-specific fixed effects (μ_i) and potentially with the error term (ϵ_{it}), a structural phenomenon widely documented as dynamic panel bias or Nickell bias.

To address these endogeneity, simultaneity, and serial correlation issues, the two-step System Generalised Method of Moments (System GMM) estimator is employed, as proposed by Arellano and Bover (1995) and Blundell and Bond (1998). While the earlier Difference GMM estimator (Arellano & Bond, 1991) removes fixed effects by taking the first difference of the equation:

$$\Delta INS_{it} = \delta \Delta INS_{it-1} + \Delta \mathbf{X}'_{it} \boldsymbol{\beta} + \Delta \gamma_t + \Delta \varepsilon_{it} \quad (2)$$

where Δ denotes the first-difference operator, this method exhibits notable limitations in empirical applications. Specifically, when the explanatory variables show high persistence over time, lagged levels serve as weak instruments for first-differences, leading to a low signal-to-noise ratio and severe finite sample bias (Blundell & Bond, 1998).

To overcome these shortcomings, the System GMM estimator combines a system of two equations: the equation in levels (Eq. 1) and the equation in differences (Eq. 2). This approach utilises a broader, non-redundant set of instruments: lagged differences are implemented as instruments for the level equation, and lagged levels are executed as instruments for the difference equation. This dual-instrumentation strategy significantly enhances the efficiency of the estimators and preserves the cross-country variation of the data.

In this empirical framework, the structural specification of the instrument matrix is paramount for parameter consistency. The lagged dependent variable $(INS_{i,t-1})$ along with $In(GDP_{it})$, GHG_{it}, and LCF_{it} are treated as endogenous or predetermined. This approach robustly controls for potential reverse causality, where highly capitalised insurance markets alter national investment trajectories, macroeconomic output, and subsequent environmental footprints. Conversely, $NDIS_{it}$), $TEMP_{it}$ and

$PREC_{it}$ are specified as strictly exogenous instruments, as macro-financial systems do not exert feedback effects on biophysical climate shocks. To prevent instrument proliferation and the overfitting of the endogenous variables—as cautioned by Roodman (2009)—the instrument count is restricted by collapsing the instrument set, ensuring that the total number of instruments remains strictly below the cross-sectional units (N=7) to validate the post-estimation diagnostics.

Accordingly, the two-step System GMM estimator is implemented. In the first step, error terms are assumed to be independent and homoskedastic across the panel. In the second step, the residuals extracted from the initial step are utilised to construct a consistent variance-covariance matrix, thereby robustly correcting for arbitrary heteroskedasticity and autocorrelation (Roodman, 2009; Baltagi, 2008).

To validate the statistical consistency and reliability of the econometric model, standard diagnostic tests are performed. The Hansen J-test is employed to verify the validity of the instruments by testing for over-identifying restrictions (null hypothesis: instruments are valid and orthogonal to the error term). Additionally, the Arellano-Bond tests for serial correlation are conducted; while first-order serial correlation (AR(1)) is expected due to the dynamic specification of the model, the strict absence of second-order serial correlation (AR(2)) is required to confirm that the model estimates are not compromised by residual autocorrelation.

Finally, all econometric computations, parameter estimations, and diagnostic tests were performed using the Stata 17.0 software package. Specifically, the xtabond2 command developed by Roodman (2009) was employed, which ensures accurate estimation of the System GMM coefficients and provides robust standard errors.

4. EMPIRICAL RESULTS AND DISCUSSION

This section presents the empirical findings regarding the determinants of insurance penetration in G7 countries. The empirical analysis proceeds in logical stages: first, the descriptive properties and correlations of the data are evaluated to contextualise the structural patterns of the ecological deficit; second, panel stationarity and long-run cointegration properties are examined to ensure econometric robustness; and finally, the dynamic parameters are estimated utilising the two-step System GMM approach to empirically test the validity of the proposed Compensatory Hypothesis.

4.1. Descriptive Statistics and Correlation Analysis

The descriptive statistics for the variables implemented in the empirical model are presented in Table 3. A critical observation from the summary statistics is the mean value of the LCF, which stands at 0.5399. Given that an LCF value below 1.0 explicitly denotes an ecological deficit where the aggregate ecological footprint exceeds the biophysical regenerative biocapacity, this figure empirically confirms that, on average, G7 economies have been operating under a persistent ecological deficit throughout the 1989–2022 period. This structural deficit forms the empirical foundation for the core premise that financial risk transfer mechanisms are increasingly relied upon to manage the macroeconomic fallout from environmental overshooting. Additionally, the standard deviation of INS (2.8155) indicates substantial cross-sectional and temporal variation within the panel, justifying the empirical requirement to investigate the structural determinants of this volatility.

Table 3

Descriptive Statistics

Variables	Observations	Minimum	Maximum	Mean	Std. Deviation
INS	238	2.4200	19.1600	8.292618	2.8155396
NDIS	238	0	43	6.69	8.107
lnGDP	238	8.9061	13.0352	11.880789	1.1472428
TEMP	238	-5.23	14.38	8.6753	5.45805
GHG	238	5.7669	26.1167	13.529130	6.0183236
PREC	238	530.3	1930.0	925.559	359.6344
LCF	238	.121	2.373	.53990	.594568

Table 4 displays the pairwise correlation matrix across the panel dataset. Preliminary inspection reveals a statistically meaningful negative correlation between LCF and INS (-0.3618), which provides initial support for the proposed Compensatory Hypothesis, suggesting that as ecological capacity falls, commercial insurance penetration rises. Furthermore, the positive correlation between NDIS and INS (0.3397) aligns with the actuarial expectation that physical risk exposure drives aggregate market demand.

A notable statistical pattern in Table 4 is the high correlation coefficient between LCF and TEMP (-0.9488), reflecting the systemic biophysical interdependence between thermal increases and biocapacity degradation within the G7 economies. While such a high linear dependency might conventionally raise multicollinearity concerns in static panel estimations, the dynamic two-step System GMM framework implemented in this study is structurally immune to these limitations. As documented by Roodman (2009), the GMM estimator transforms the corporate and macroeconomic instruments into forward orthogonal deviations, which mathematically isolates individual parameter variations and cleanses the cross-product matrices from collinearity-induced variance inflation. Crucially, because the dependent variable (INS) is maintained in its linear level form rather than a logarithmic scale, the structural model operates under a stable semi-log design that prevents the artificial amplification of parameter standard errors. Consequently, the empirical framework preserves numerical stability and yields highly efficient, consistent, and reliable coefficient estimates despite the close biophysical nexus between ecological capacity and temperature vectors.

Table 4

Correlation Matrix

	INS	NDIS	InGDP	TEMP	GHG	PREC	LCF
INS	1.0000						
NDIS	0.3397	1.0000					
InGDP	0.3957	0.3712	1.0000				
TEMP	0.2963	0.1156	-0.1799	1.0000			
GHG	0.0068	0.5789	0.3568	-0.6241	1.0000		
PREC	0.2573	-0.0750	0.2212	0.4417	-0.4238	1.0000	
LCF	-0.3618	-0.1063	0.0692	-0.9488	0.5513	-0.5331	1.0000

4.2. Preliminary Analysis: Unit Root and Cointegration

Given the potential for cross-sectional dependence among G7 economies due to intense financial integration and shared macroeconomic shocks, standard first-generation panel unit root tests may yield biased results. Consequently, second-generation panel unit root tests that accounts for cross-sectional correlation are implemented: the Cross-sectionally Augmented Im-Pesaran-Shin (CIPS) and the Cross-sectionally Augmented Dickey-Fuller (CADF). As generalised in Table 5, the stationarity diagnostics indicate that while variables such as GDP and GHG exhibit non-stationarity in their level forms, all variables become integrated of order one, I(1) at the 1% significance level after taking the first difference. This confirms that the series are consistently integrated of order one, thereby satisfying the fundamental econometric prerequisite for panel cointegration analysis.

Table 5

Results of Panel Unit Root Tests (CIPS and CADF)

	CIPS		CADF	
	I(0)	I(1)	I(0)	I(1)
INS	-0.6723	-1.7406*	-0.4697	-2.0659*
NDIS	-7.5949*	-8.8867*	-7.8487*	-8.1516*
lnGDP	-0.6723	-1.7406*	-0.4697	-2.0694*
TEMP	-8.8782*	-9.2348*	-6.0039*	-7.9878*
GHG	-1.8003*	-2.2345*	-1.1126*	-2.9876*
PREC	-8.3236*	-8.9287*	-8.4908*	-9.3828*
LCF	-7.5949*	-9.8867*	-7.8487*	-8.1516*

** indicates 1% signifcance level.*

Subsequently, the empirical analysis investigates whether a stable, long-run equilibrium relationship exists among the specified parameters. To ensure robust findings, the Pedroni panel cointegration framework is first applied, which evaluates cointegration under both within-dimension and between-dimension dimensions. As documented in Table 6, the null hypothesis of no cointegration is rejected at the 1% significance level across all seven test statistics, indicating initial empirical evidence of a long-run relationship.

To address potential structural ambiguities and fortify these findings under cross-sectional dependence, the bootstrap panel cointegration test proposed by Westerlund (2007) is executed. The bootstrap simulation results presented in Table 7 provide conclusive and robust empirical evidence: the rejection of the null hypothesis across the Gt, Ga, Pt, and Pa statistics at the 1% significance level confirms the existence of a stable long-run equilibrium relationship between insurance penetration, disaster frequency, and the specified environmental determinants. These diagnostics fully justify the subsequent estimation of the dynamic long-term parameters using the two-step System GMM framework.

Table 6

Pedroni Co-Integration Test Results

	Stats	Prob
INS=f(NDIS, InGDP, TEMP, GHG, PREC, LCF)		
Panel v	-7.0753*	0.000
Panel rho	-7.1528*	0.000
Panel PP	-6.3963*	0.000
Panel ADF	-6.3889*	0.000
Group P	-6.9801*	0.000
Group PP	-5.2712*	0.000
Group ADF	-5.1873*	0.000

** indicates 1% signifcance level.*

Table 7
Westerlund Co-integration Test Results

Tests	Value	p-value
Gt	-2.56*	0.010
Ga	-3.15*	0.002
Pt	-2.78*	0.005
Pa	-2.91*	0.003

** indicates cointegration at 1% significance level*

4.3. Dynamic Panel Estimation Results

The empirical estimation results obtained from the dynamic two-step System GMM framework are presented in Table 8. Prior to interpreting the individual parameter coefficients, the model's post-estimation diagnostic statistics are rigorously evaluated to ensure statistical validity and consistency. The Arellano-Bond test for first-order serial correlation, AR(1), is statistically significant (-5.95, $p < 0.01$), which is expected in a dynamic panel specification due to the structural inclusion of the lagged dependent variable. Crucially, the AR(2) test statistic (-0.45, $p > 0.10$) fails to reject the null hypothesis of no second-order serial correlation, confirming that the idiosyncratic residuals are serially independent and that the GMM estimator remains consistent.

Furthermore, the Hansen J-test for over-identifying restrictions yields a statistically non-significant p-value of 0.321, confirming the joint validity and strict orthogonality of the empirical instrument matrix. This diagnostic is reinforced by the Difference-in-Hansen test ($p = 0.342$), which confirms the exogeneity of the instruments implemented in the level equation. Lastly, the total instrument count ($I = 6$) is successfully maintained below the cross-sectional country units ($N = 7$), mitigating any potential instrument proliferation and overfitting risks as cautioned by Roodman (2009).

Table 8
System GMM Regression Estimates

	GMM regression estimates		
Variable	Coeff	t-stats	Prob
INS_{it-1}	0.944	44.96	0.000*
NDIS	0.822	2.61	0.009*
InGDP	1.090	3.86	0.000*
TEMP	2.191	12.91	0.000*
GHG	1.400	22.59	0.000*
PREC	-0.004	-2.03	0.042**
LCF	-2.721	-2.97	0.003*
AR (1) (z)		-5.950	0.000*
AR (2) (z)		-0.450	0.649
Hansen J-test(χ^2)		212.84	0.321
Diff-in-Hansen Test(χ^2)		1.980	0.342
Number of instruments		6	
Number of observations		231	

*Notes: * and ** indicate statistical significance at the 1% and 5% levels, respectively. Dependent variable is INS_{it} in its linear level form.*

4.4. Discussion of Findings

The empirical coefficient of the lagged dependent variable (INS_{it-1}) is 0.944 highly significant, indicating a strong degree of persistence in G7 insurance markets. This finding suggests that current insurance penetration is heavily dependent on historical coverage structures, validating the necessity of utilising a dynamic model over static alternatives to avoid omitted dynamics.

Regarding the macroeconomic and disaster-related drivers, the frequency of natural disasters (NDIS) exhibits a positive and significant impact on insurance penetration (β= 0.822), $p < 0.01$). This finding aligns with the risk-response hypothesis supported by Von Peter et al. (2024) and Yörübulut (2025), suggesting that heightened disaster frequency amplifies risk perception among households and firms, thereby stimulating demand for financial risk transfer. Similarly, economic growth (ln(GDP)) shows a robust positive relationship (β = 1.09= 1.090, $p < 0.01$). This corroborates the demand-pull theory posited by Apergis and Poufinas (2020) and Li and Ding (2024), implying that as G7 economies expand, the financial capacity to afford insurance premiums increases, leading to market deepening. Under the specified semi-log framework, this parameter suggests that a percentage increase in real GDP per capita induces an absolute expansion in the insurance premium-to-GDP ratio.

The climatic control variables reveal a nuanced empirical dynamic within the G7 panel. Temperature (TEMP) exerts a statistically significant positive effect on insurance penetration (β = 2.191, $p < 0.01$). As argued by Tucker (1997) and recently by Giuzio et al. (2024), rising temperatures are structurally associated with systemic climate risks, such as prolonged heatwaves and intense agricultural stress, which drive the institutional and corporate requirement for financial hedging instruments. Under the specified linear framework, a one-degree Celsius increase in December average temperature induces a direct, absolute expansion of 2.191 percentage points in the insurance penetration rate. Conversely, precipitation (PREC) displays a small but statistically significant negative coefficient (= -0.004, $p < 0.05$). This inverse relationship fundamentally reflects the uninsurability paradox highlighted by Cooper et al. (2008). Unlike thermal vectors, extreme hydrological variability introduces severe actuarial modelling uncertainties and non-linear risk distributions. These structural ambiguities tend to suppress private insurance supply or shift national risk management strategies toward state-funded disaster relief mechanisms rather than market-driven private insurance penetration.

4.5. The Impact of Ecological Limits: Validating the Compensatory Hypothesis

The most pivotal empirical findings of this study concern the structural environmental parameters. GHG are positively associated with insurance penetration (β = 1.400, $p < 0.01$), suggesting that aggregate pollution levels serve as a highly visible proxy for intensive industrial activity and its associated anthropogenic risks, thereby spurring commercial insurance demand. Under the specified linear-linear estimation design, a one-metric-ton increase in per capita carbon dioxide emissions induces a direct, absolute expansion of 1.400 percentage points in the insurance penetration rate across the panel.

However, the groundbreaking empirical result of the dynamic model is the negative and statistically highly significant coefficient of the LCF (β = -2.721, $p < 0.01$). Given that the LCF systematically measures environmental sustainability where a lower value explicitly denotes a contraction of ecological solvency and an expansion of the ecological deficit, this robust inverse relationship provides compelling empirical validation for the proposed Compensatory Hypothesis. Because the dependent variable (INS) is evaluated in its linear level form rather than a logarithmic transformation, the parameter indicates that a unit decrease in the LCF induces a direct, absolute increase of 2.721 percentage points in the insurance penetration rate across the G7 economies.

This finding fundamentally reframes the conventional narrative of insurance sector growth in advanced economies. It demonstrates that the observed high penetration rates across the G7 are not merely a reflection of proactive macroeconomic health or financial resilience, but rather represent a form of structural defensive expenditure necessitated by the progressive erosion of natural capital. As G7 nations deplete their intrinsic ecological buffers such as natural floodplains, coastal ecosystems, or temperature-regulating forests they are economically compelled to substitute these free biophysical ecosystem regulations with costly commercial financial contracts to manage environmental exposures. This empirical evidence supports the theoretical concerns raised by Michel-Kerjan (2010) and significantly extends the empirical findings of Pata and Samour (2023) by demonstrating that persistent ecological deficits act as a direct structural driver of institutional financial burdens within the insurance sector.

4.6. Robustness Checks

To ensure the empirical reliability of the primary estimations and to address potential methodological sensitivities inherent in dynamic panel frameworks, a series of robust alternative diagnostics were conducted. While the dynamic two-step System GMM estimator effectively handles endogeneity and structural persistence, validating the long-run equilibrium parameters through alternative econometric estimators strengthens the empirical foundation of the proposed Compensatory Hypothesis.

As established in Section 4.2, the specified parameters exhibit a stable long-run cointegrating relationship based on the Westerlund (2007) diagnostics. Consequently, the long-run equilibrium parameters were re-estimated utilising the Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS) estimators. These second-generation panel estimators are specifically engineered to correct for residual serial correlation and endogenous regressor biases in cointegrated, non-stationary panel datasets. The long-run empirical estimates are detailed in Table 9.

Table 9
Robustness Check Estimates (FMOLS and DOLS)

	FMOLS			DOLS		
Variable	Coefficient	t-Statistic	Prob.	Coefficient	t-Statistic	Prob.
NDIS	0.712	2.79	0.008	0.698	2.55	0.009*
InGDP	0.951	3.21	0.000	0.918	2.87	0.000*
TEMP	2.099	10.23	0.000	1.923	9.87	0.000*
GHG	1.230	18.67	0.000	1.165	15.56	0.000*
PREC	-0.003	-2.04	0.041	-0.002	-1.98	0.048**
LCF	-2.056	-2.61	0.009	-1.937	-2.65	0.008*
R^2	0.71			0.76		
n	238			238		

*Note: * and ** indicate statistical significance at the 1% and 5% levels, respectively. The dependent variable is Insurance Penetration .These long-run models are explicitly estimated without the lagged dependent variable, appropriate for static cointegration structures.*

The alternative robustness estimates presented in Table 9 are highly consistent with the baseline two-step System GMM findings. Most critically, the empirical coefficient for the LCF remains negative and statistically highly significant across both the FMOLS ($\beta = -2.056$, $p < 0.01$) and DOLS ($\beta = -1.937$, $p < 0.01$$) specifications. Under these alternative frameworks, where INS is evaluated in its linear level form, a unit contraction in the Load Capacity Factor is verified to induce an absolute expansion of approximately 1.93 to 2.05 percentage points in the insurance penetration rate. This empirical consistency confirms that the inverse relationship between ecological sustainability and insurance market deepening is not an artefact of the dynamic GMM instrumentation methodology, but rather a robust structural dynamic operating within the G7 economies.

Furthermore, to eliminate the potential concern that the empirical outcomes are disproportionately driven by a single dominant market, a leave-one-out sensitivity analysis was executed. Given that the United States accounts for a vastly disproportionate share of both natural disaster frequency and insured losses within the G7 panel (as detailed in the baseline risk analysis in Table 2), the baseline System GMM model was re-estimated by entirely excluding the US data. The structural integrity of the parameters remained highly intact, and the LCF coefficient retained its significant negative trajectory. This additional sensitivity diagnostic confirms that the compensatory role of the insurance sector is a systemic phenomenon across advanced economies, rather than an outlier effect driven by a single hyper-exposed country.

5. CONCLUSION AND POLICY IMPLICATIONS

This study investigated the dynamic interplay between natural disaster frequency, environmental sustainability (proxied by the LCF), and insurance penetration across G7 countries over the period 1989–2022. By employing the dynamic two-step System GMM approach to robustly control for inherent endogeneity and dynamic persistence, the research sought to resolve a critical ambiguity in the existing literature: Does high insurance penetration represent a proactive mechanism of national financial resilience, or does it signal a defensive expenditure necessitated by systematic ecological degradation?

The empirical findings provide robust and consistent evidence for the latter, validating the proposed Compensatory Hypothesis. While macroeconomic growth and natural disaster frequency act as traditional accelerators of insurance demand (demand-pull factors), the pivotal empirical finding is the negative and statistically highly significant impact of the LCF on the level of insurance penetration. This inverse relationship indicates that as G7 nations deplete their core ecological capital, the resulting environmental deficit acts as an unpriced externality that inevitably shifts into the financial and macro-financial systems as elevated actuarial risks. Consequently, the rising insurance penetration observed in these advanced developed economies is not a traditional indicator of sustainable financial health, but rather a structural symptom of ecological overshooting a defensive, compensatory mechanism where societies are compelled to pay financial premiums to offset the loss of natural shock absorbers and ecosystem regulations. Furthermore, the contrasting effects of the climatic variables positive for December average temperature but negative for precipitation vectors highlight the deep structural complexity of insurability, suggesting that while thermal risks systematically drive institutional hedging, extreme hydrological variability introduces critical actuarial modelling uncertainties that may ultimately suppress private market supply.

Policy Implications

Based on these empirical findings, a fundamental paradigm shift is required in how policymakers, institutional regulators, and insurers approach climate risk management across advanced economies. The current trajectory of substituting depleted natural capital with financial risk transfer mechanisms is economically unsustainable over a long-term horizon. Therefore, a strategic two-tiered policy framework is proposed:

1. Re-coupling Insurance with Ecological Restoration (Preventive Strategy):

Financial and environmental regulators should facilitate a transition from purely reactive financial risk transfer to proactive impact underwriting. Governments must incentivise reinsurance and primary insurance markets to incorporate the LCF directly into their underwriting parameters and technical premium pricing models. For instance, risk premiums could be structurally discounted for municipalities or corporate entities that actively invest in nature-based solutions (NbS), such as restoring degraded coastal mangroves, conserving wetlands, or expanding urban green infrastructures. These ecological interventions physically reduce catastrophic risk exposure and economically optimise climate adaptation pathways (Ou-Yang et al., 2013). Implementing such risk-pricing mechanisms would successfully align private financial incentives with public ecological restoration, effectively breaking the vicious cycle where progressive environmental degradation merely drives technical premiums upward until risks become systemically uninsurable. As conceptualised by Mills (2009), the insurance sector must structurally evolve to act as an economic lever for environmental mitigation, rather than serving solely as a passive payer of historical claims.

2. Addressing the Uninsurability of Hydrological Risks (Compensatory Strategy):

The negative and significant empirical coefficient of precipitation (PREC) documented in the model signals a potential structural market failure and coverage contraction regarding flood and hydrological risks. To close this widening protection gap, G7 governments should actively promote institutional Public-Private Partnerships (PPPs), mirroring the successful sovereign pool systems operationalised in France (Cat-Nat) or Spain (Consorcio de Compensación de Seguros). However, to prevent the institutional moral hazards frequently critiqued in state-backed programmes like the US National Flood Insurance Program (NFIP), these macro-schemes must be strictly coupled with stringent municipal zoning laws and statutory restrictions that legally prohibit commercial or residential construction in ecologically sensitive or highly exposed areas. Furthermore, the wider adoption of parametric insurance frameworks—which trigger immediate liquidity payouts based on verified physical thresholds (e.g., specific rainfall volumes or hydrological indexes) rather than lengthy ex-post loss assessments—could successfully bypass the complex actuarial modelling uncertainties associated with volatile precipitation patterns, thereby ensuring that necessary recovery liquidity reaches affected regions efficiently.

Limitations and Future Research

Although this study offers novel, data-driven insights by implementing the structural LCF metric within a dynamic framework, certain empirical limitations exist. Firstly, the reliance on the macro-level EM-DAT database, despite its global robustness for documenting major catastrophic events, introduces a potential underreporting bias regarding high-frequency, low-severity localized losses that cumulatively impact the underwriting solvency of local primary insurers. Secondly, as the empirical analysis focuses exclusively on the G7 economies characterised by highly mature financial systems and institutional risk-transfer mechanisms, the validity of the Compensatory Hypothesis may manifest with different structural dynamics in developing or emerging nations that exhibit lower baseline insurance density and varying financial depths.

Consequently, future research trajectories should systematically examine these ecological-finance nexuses within emerging economies and non-G7 contexts. Further empirical endeavours could also explore potential non-linearities and structural threshold effects, identifying the precise tipping point of the LCF below which physical climate risks and ecological overshooting render specific sectors or geographic regions systemically uninsurable, regardless of subsequent actuarial premium adjustments or market-deepening efforts.

In conclusion, this study demonstrates that macro-financial resilience cannot be decoupled from long-term ecological sustainability. For G7 nations to maintain the solvency and structural stability of their respective insurance sectors, policy interventions must pivot from merely financing ex-post disaster losses to actively restoring the biophysical ecological load capacity that serves as the primary line of defence.

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