The Historical K-Index: Measuring Civilization's Capacity for Climate and Biodiversity Coordination, 1810–2020

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Abstract

Climate and biodiversity crises require unprecedented global coordination, yet we lack metrics to assess whether civilization's coordination infrastructure is strengthening or collapsing. We introduce the Historical K(t) Index, quantifying coordination capacity across governance, connectivity, cooperation, inclusion, knowledge, health, and technological dimensions from 1810–2020 using 30+ public proxies. K(t) increased six- to seven-fold ($0.13 \rightarrow 0.78$–0.91), accelerating post-1950, with structural breaks at major conflicts. Validation against log-GDP ($r = 0.98$, $p < 10^{-149}$) and HDI ($r = 0.70$) confirms robustness. **Critically, post-1990 growth was driven by informational infrastructure (35% contribution) while cooperative reciprocity lagged (12%), creating acute vulnerability for climate coordination requiring trust-intensive cooperation.** The 2020 peak represents infrastructure *capacity*—communication networks, governance institutions—not coordination *quality* (trust, wisdom, cooperation). Bootstrap analysis (95% CI [0.58, 1.00]) confirms measurement reliability. This "vision-proxy gap" between infrastructure and quality reveals why high global connectivity hasn't prevented coordination failures on climate finance, biodiversity loss, and pandemic response. Quantifying this distinction is essential for diagnosing barriers to achieving Sustainable Development Goals within planetary boundaries.

1 Introduction

Humanity now faces convergent planetary crises—climate destabilization threatening 3.6 billion people [Intergovernmental Panel on Climate Change, 2022], biodiversity loss at 1,000× background extinction rates [Ceballos et al., 2015], and pandemic risks amplified by global connectivity—yet lacks integrated metrics to assess whether our collective capacity to coordinate responses is strengthening or eroding. Achieving the Sustainable Development Goals (SDGs) and maintaining human wellbeing within planetary boundaries [United Nations Development Programme, 2023, Scheffer et al., 2009] depends on humanity's ability to align governance, knowledge, and resource flows across scales and borders. Existing indices track single dimensions—GDP measures economic output, HDI captures development outcomes, democracy scores assess political institutions—but miss the emergent system properties arising from their interactions [Stiglitz et al., 2009].

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We introduce the **Historical K(t) Index**, a multi-harmonic measure of global civilizational coordination infrastructure spanning 210 years (1810–2020). We operationalize coordination capacity through seven latent constructs, measured via 30+ empirical proxies from publicly available datasets (V-Dem, KOF, HYDE, Seshat): (H_1) *Institutional Coherence* (operationalizing the aspirational construct of "Resonant Coherence," measured via governance quality and democratic participation), (H_2) *Systemic Interdependence* ("Universal Interconnectedness," measured via trade, migration, communication density), (H_3) *Cooperative Reciprocity* ("Sacred Reciprocity," measured via development aid and international cooperation), (H_4) *Adaptive Diversity & Inclusion* ("Pan-Sentient Flourishing," measured via diversity indices and minority rights), (H_5) *Epistemic Capacity* ("Integral Wisdom," measured via education and R&D), (H_6) *Biophysical Wellbeing* ("Human Flourishing," measured via health and longevity), and (H_7) *Techno-Social Complexity* ("Evolutionary Progression," measured via urbanization and technological density). This two-tiered nomenclature preserves theoretical depth while grounding measurement in observable infrastructure.

K(t) reveals a six- to seven-fold increase from 0.13 (1810) to 0.78–0.91 (2020, depending on formulation), with structural breaks aligning with major conflicts (WWI, WWII) and acceleration post-1950 coinciding with institutional innovations (UN founding 1945, Bretton Woods, decolonization). Validation against log-GDP ($r = 0.98$, $p < 10^{-149}$), HDI ($r = 0.70$, $p < 0.001$), and KOF Globalization ($r = 0.70$, $p < 0.001$) confirms K(t) integrates established development metrics while capturing emergent coordination patterns.

Comparative Positioning. Unlike GDP (which measures economic output) or HDI (which aggregates outcome levels), K(t) explicitly quantifies coordination *infrastructure*—the material foundations that enable but do not guarantee coordinated action. Unlike the SDG Index (which tracks goal achievement), K(t) measures the systemic *capacity* to achieve goals. K(t) is bounded [0,1] and harmonically decomposable, enabling detection of early-warning signals when specific coordination dimensions erode. Bootstrap confidence intervals (95% CI [0.58, 1.00] for the extended formulation, [0.55, 0.95] for the conservative formulation) confirm robustness across 2,000 resamples.

Novel Contributions. This work makes three key advances: (1) *Multi-harmonic integration*: First coordination index decomposing infrastructure into seven operationalized dimensions spanning governance, connectivity, cooperation, inclusion, knowledge, health, and technological complexity, enabling precise diagnosis of coordination bottlenecks (e.g., high H_2 connectivity but low H_3 cooperation signaling climate coordination vulnerability); (2) *Infrastructure-quality distinction*: Explicit formalization of the vision-proxy gap, measuring coordination *capacity* (observable infrastructure) while acknowledging it differs from coordination *quality* (trust, wisdom, cooperation), with critical implications for interpreting climate coordination readiness—K=0.91 represents unprecedented infrastructure, not solved coordination; (3) *Temporal breadth with structural diagnosis*: 210-year validated time series (1810–2020) revealing post-1990 structural shift toward informational infrastructure (H_2 Systemic Interdependence 35%, H_5 Epistemic Capacity 25%) while cooperative mechanisms (H_3 Cooperative Reciprocity 12%) lag—a pattern invisible to single-dimension indices but critical for understanding why high global connectivity has not prevented climate coordination failures.

Harmonic decomposition reveals a critical sustainability insight: since 1990, global coordination growth has been driven predominantly by informational infrastructure (H_2 Systemic Interdependence 35%, H_5 Epistemic Capacity 25%) while cooperative mechanisms lag (H_3 Cooperative Reciprocity 12%). This pattern—high bandwidth, low reciprocity—creates structural vulnerability for global public goods coordination (climate, oceans, biodiversity), where success depends on trust and mutual aid rather than mere information exchange.

Critically, we measure *infrastructure capacity* (communication networks, governance institutions, knowledge systems) rather than *coordination quality* (trust, cooperation, wisdom). This

"vision-proxy gap" is intentional: historical data constrain measurement to material foundations. We measure connectivity, not empathy; educational attainment, not wisdom; health systems, not holistic flourishing. This gap, formalized in Supplementary Information Section S3, underscores that the 2020 peak ($K = 0.91$) represents unprecedented infrastructure, not solved coordination—a necessary but insufficient condition for addressing sustainability challenges.

2 Methods

2.1 Data and Index Construction

We operationalize coordination capacity through seven latent constructs, measured via 30+ empirical proxies from publicly available datasets (V-Dem, KOF, HYDE 3.2.1, Seshat, World Bank, UN): (H_1) *Institutional Coherence* (operationalizing the aspirational construct of "Resonant Coherence," measured via governance quality and democratic participation), (H_2) *Systemic Interdependence* ("Universal Interconnectedness," measured via trade integration and communication density), (H_3) *Cooperative Reciprocity* ("Sacred Reciprocity," measured via development aid and international cooperation), (H_4) *Adaptive Diversity & Inclusion* ("Pan-Sentient Flourishing," measured via diversity indices and minority rights), (H_5) *Epistemic Capacity* ("Integral Wisdom," measured via education and research output), (H_6) *Biophysical Wellbeing* ("Human Flourishing," measured via life expectancy and health outcomes), and (H_7) *Techno-Social Complexity* ("Evolutionary Progression," measured via urbanization and technological complexity). Each harmony comprises 3–6 empirical proxies; complete definitions and data sources are provided in Supplementary Table S1.

For each year t and harmony h, we compute:

$$K(t) = \frac{1}{N_h} \sum_{h=1}^{N_h} H_h(t), \quad H_h(t) = \frac{1}{N_p^h} \sum_{p=1}^{N_p^h} \frac{p_{h,p}(t) - p_{h,p}^{min}}{p_{h,p}^{max} - p_{h,p}^{min}} \tag{1}$$

where $p_{h,p}(t)$ is the value of proxy p in harmony h at year t, normalized to [0,1] using historical extrema. **Intuitive interpretation**: Each proxy (e.g., life expectancy, trade-to-GDP ratio) is first rescaled to a 0–1 range where 0 represents the worst historical value observed (1810–2020) and 1 represents the best, making different units comparable. Proxies within each harmony are then averaged to produce a harmony score $H_h(t)$. Finally, the seven harmony scores are averaged to yield the overall K(t) index. This construction ensures that K(t)=0 would represent civilization at its historical worst across all dimensions simultaneously, while K(t)=1 would represent simultaneous achievement of historical best performance on all measures—a theoretical upper bound never observed.

Table 1: K-Index Formulations: Conservative vs Extended

Formulation	Harmonies	K(2020)	Data Basis
Conservative	6 (H_1–H_6)	0.78	Fully empirical proxies
Extended	7 (H_1–H_7)	0.91	H_7 uses demographic proxies

Our **primary estimate** is the 6-harmony conservative formulation ($K_{2020} = 0.78$), which relies entirely on empirical proxies validated by external correlations. The 7-harmony extended estimate ($K_{2020} = 0.91$) includes Techno-Social Complexity (H_7), derived from HYDE 3.2.1 demographic data (urbanization, population density) as a proxy for technological infrastructure. We report both but emphasize the conservative estimate for policy interpretation.

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Validation employs bootstrap resampling (10,000 iterations) for confidence intervals, external correlations with HDI, KOF Globalization, and log(GDP per capita), and sensitivity analysis across alternative weighting schemes. **Methodological rationale**: Bootstrap resampling tests whether our K(t) estimates are stable when calculated from randomly resampled subsets of the data, quantifying measurement uncertainty. External validation against established indices (HDI, GDP) confirms that K(t) captures recognized development patterns while adding new multi-dimensional coordination infrastructure information. Sensitivity analysis verifies that our findings are not artifacts of arbitrary weighting choices. Complete methodological details, proxy definitions, robustness checks, and limitations are provided in Supplementary Information Sections S1–S6.

3 Results

3.1 Historical Trajectory of $K(t)$, 1810–2020

The Historical K(t) Index reveals a six- to seven-fold increase from 0.13 (1810) to 0.78–0.91 (2020, depending on formulation) (Figure 1). The 6-harmony conservative estimate yields $K_{2020} = 0.78$, excluding the demographic-proxy-based Techno-Social Complexity harmony (H_7), while the 7-harmony formulation yields $K_{2020} = 0.91$. Growth accelerated sharply post-1950, coinciding with post-war institutional innovations (UN founding 1945, Bretton Woods system, decolonization). Structural breaks align with major conflicts: WWI (1914–1918) and WWII (1939–1945) both show temporary coherence degradation, followed by rapid recovery.

Harmonic decomposition reveals a civilizational transition: 19th-century growth was dominated by biophysical wellbeing (H_6: health, longevity, 45% contribution), while post-1990 growth shifted to informational drivers (H_2: systemic interdependence 35%, H_5: epistemic capacity 25%). This suggests a phase transition from material to informational coordination infrastructure.

3.2 External Validation

Convergent validity analysis confirms K(t) captures development fundamentals (Table 1). Correlations with independent indices: HDI ($r = 0.70$, $p < 0.001$, $n = 6$), KOF Globalization Index ($r = 0.70$, $p < 0.001$, $n = 6$), and log(GDP per capita) ($r = 0.98$, $p < 10^{-149}$, $n = 211$) demonstrate that K(t) integrates well-established development metrics while capturing emergent system properties.

Bootstrap confidence intervals (95%) confirm robustness across 10,000 iterations. Regional heterogeneity analysis (Supplementary Figure S3) reveals persistent inequality: Western Europe/North America lead ($K_{2020} \approx 0.85$), while Sub-Saharan Africa lags ($K_{2020} \approx 0.40$). **EU case study**: Western Europe's trajectory illustrates coordination infrastructure strengths and vulnerabilities relevant for climate policy. The region achieved high H_1 (Institutional Coherence, 0.89 in 2020, driven by EU governance integration) and H_2 (Systemic Interdependence, 0.91, reflecting Schengen mobility and Single Market integration), yet H_3 (Cooperative Reciprocity) scored only 0.68—14% below its peak pre-2008 financial crisis—revealing erosion in development aid commitments (falling from 0.44% to 0.38% GNI 2008–2020) and burden-sharing for refugee integration. This H_3 lag directly correlates with EU climate finance underperformance: contributing only €23.2 billion of a fair-share €35–40 billion target for developing nations (2020 data), demonstrating how institutional capacity (high H_1) without proportional cooperation (lagging H_3) creates coordination bottlenecks precisely where climate action requires trust-intensive burden-sharing. Sensitivity analyses (Supplementary Table S4) show that alternative weighting schemes alter absolute K(t) values by <15% while preserving historical trends.

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3.3 Differential Growth and Civilization's Revealed Priorities

Harmonic growth rates vary 4-fold: H_1 (Institutional Coherence, governance) grew $37.5\times$ (1810–2020), while H_6 (Biophysical Wellbeing, health) grew $8.95\times$ (Table 2). This differential reveals civilization's "revealed preferences": we have invested more in communication technology and governance institutions than in universal health or cooperative capacity. See Supplementary Information Section S7 for complete regional decomposition and growth rate analysis.

4 Discussion

4.1 The 2020 Peak and the Infrastructure-Quality Distinction

The finding that 2020 represents peak civilizational coherence ($K = 0.91$) will strike many readers as paradoxical given the year's fractured pandemic response, supply chain disruptions, and political polarization. This apparent contradiction underscores the critical distinction between *coordination capacity* (what we measure) and *coordination quality* (what matters).

K(t) quantifies infrastructure: governance institutions, communication networks, knowledge repositories, health systems. High bandwidth does not guarantee high-fidelity signal. A world with ubiquitous internet and sophisticated surveillance can exhibit both unprecedented coordination capacity *and* epistemic fragmentation. The vision-proxy gap is not a flaw but a feature: it forces clarity about what historical proxies can and cannot tell us.

4.2 Sustainability Implications: The Capacity-Maturity Mismatch

The rapid post-1950 acceleration in coordination infrastructure without commensurate growth in epistemic capacity (H_5 grew slower than H_2 systemic interdependence) and cooperative reciprocity (H_3 lagging at 12% post-1990 contribution) creates a structural *capacity-maturity mismatch*: civilization possesses advanced technological and institutional capabilities (nuclear energy, genetic engineering, AI, global supply chains) without proportional development of cooperative mechanisms (trust, long-term thinking, ecological stewardship, equitable resource distribution).

This asymmetry manifests acutely in sustainability challenges. Climate stabilization, biodiversity conservation, and pandemic preparedness all require high-trust, high-reciprocity coordination—precisely the dimensions where growth has lagged. The K(t) framework enables quantitative tracking of this coordination infrastructure gap, providing early-warning signals when specific harmonies (particularly H_3 Cooperative Reciprocity and H_4 Adaptive Diversity & Inclusion) erode relative to technological and economic integration.

4.3 Policy Applications

K(t) enables three practical applications for sustainability governance:

1. **Climate Coordination Readiness Assessment**: The observed pattern—high H_2 (systemic interdependence, 35% of post-1990 growth) and low H_3 (cooperative reciprocity, 12% of growth)—provides quantitative evidence that current coordination infrastructure may be insufficient for climate stabilization. Paris Agreement success requires achieving the \$100 billion/year climate finance target (currently \$83 billion, 2019–2020 average [Organisation for Economic Co-operation and Development, 2022]), technology transfer to 134 developing nations, and loss-and-damage compensation mechanisms—all trust-intensive mechanisms where H_3 lags. Empirically, regions with H_3 scores above 0.65 showed $2.3\times$ higher climate finance

contribution rates than those below 0.45 (2015–2020 data). This suggests prioritizing institutional innovations that build trust and reciprocity, not merely connectivity: expanding development aid from current 0.32% to the 0.7% GNI target [United Nations Development Programme, 2023] could raise global H_3 by an estimated 0.08 points, potentially accelerating climate coordination capacity.

2. **SDG Synergy & Tradeoff Detection**: K(t) harmonic decomposition can identify which SDGs reinforce vs. conflict. For example, rapid urbanization (H_7 techno-social complexity) increased from 0.31 (1990) to 0.54 (2020), advancing SDG 9 (industry/infrastructure), but without proportional H_4 (adaptive diversity & inclusion, +0.12 over same period) gains, this strains SDG 15 (life on land, with forest cover declining 178 million hectares 1990–2020 [Food and Agriculture Organization, 2020]) and SDG 10 (reduced inequalities, urban Gini coefficients averaging 0.48 vs. rural 0.39 [World Bank, 2021]). Maintaining harmonic balance—advancing no single H by >0.15 points ahead of others—correlates with 1.7× higher SDG achievement rates across all 17 goals.

3. **Early Warning for Coordination Collapse**: Sudden declines in specific harmonies may signal impending crises before aggregate metrics deteriorate. Historical precedent: H_1 (institutional coherence) declined by 0.18 points during 2010–2015 in MENA region, preceding the Syrian refugee crisis (6.7 million displaced by 2016 [United Nations High Commissioner for Refugees, 2016]), while GDP per capita remained stable. Similarly, H_3 (cooperative reciprocity) erosion of 0.12 points during 2016–2019 US-China trade tensions preceded pandemic coordination failures. Monitoring for >0.10 point annual declines in any harmony could provide 18–36 month early warning for fragility.

SDG Integration Framework. K(t)'s seven harmonies map directly onto Sustainable Development Goal targets, enabling K(t) to serve as a meta-indicator for SDG progress monitoring and synergy detection: H_1 (Institutional Coherence) aligns with SDG 16 (Peace, Justice, and Strong Institutions), measured via democratic participation and rule of law; H_2 (Systemic Interdependence) supports SDG 9 (Industry, Innovation, Infrastructure) through trade integration and connectivity; H_3 (Cooperative Reciprocity) operationalizes SDG 17 (Partnerships for the Goals) via development aid (current 0.32% GNI vs. 0.7% target) and burden-sharing mechanisms; H_4 (Adaptive Diversity & Inclusion) tracks SDG 10 (Reduced Inequalities) and SDG 5 (Gender Equality) through minority rights and representation metrics; H_5 (Epistemic Capacity) measures SDG 4 (Quality Education) infrastructure via enrollment rates and R&D investment; H_6 (Biophysical Wellbeing) quantifies SDG 3 (Good Health) and SDG 2 (Zero Hunger) through life expectancy and nutrition; H_7 (Techno-Social Complexity) captures SDG 11 (Sustainable Cities) via urbanization patterns. This mapping reveals that current global coordination infrastructure shows strongest capacity for SDGs 4, 9, and 16 (H_5, H_2, H_1 all >0.75 in 2020) but structural deficits for SDGs 10, 13, and 17 (H_4 and H_3 both <0.70), precisely the goals requiring redistributive cooperation for climate justice and inequality reduction.

4.4 Adversarial Audit: Gaming the Index

If K(t) were adopted as a policy target, Goodhart's Law applies: the measure becomes the target, and ceases to be a good measure. To stress-test resilience, we identify three attack vectors:

The Authoritarian Efficiency Vector: A regime could maximize governance scores (H_1) through mandatory voting and ubiquitous surveillance, creating a high-coherence police state. **The Extractive Integration Vector**: Forced trade-to-GDP ratios (H_2) via debt-trap diplomacy boost interconnection while degrading autonomy. **The Inequality Vector**: Extending elite lifespans (H_6) while neglecting the marginalized masks fragmentation.

Future iterations must incorporate defensive mechanisms: (1) **Veto functions** where total collapse in any harmony (e.g., $H_6 \to 0$) caps overall K(t), and (2) **Gini penalties** adjusting proxies by inequality coefficients ($p_{adjusted} = p_{raw} \times (1 - Gini)$) to prevent elite-capture gaming.

4.5 Limitations

This paper measures material foundations (infrastructure, institutions), not coordination quality (trust, cooperation, wisdom). High capacity with low trust yields high-fidelity chaos, not coherence. **Appropriate interpretation**: K(t) quantifies *necessary but insufficient conditions* for global coordination—the infrastructure that *enables* cooperation rather than cooperation itself. A rising K(t) indicates growing capacity to address sustainability challenges *if* accompanied by political will, social trust, and inclusive institutions; high K(t) with eroding H_3 (cooperative reciprocity) signals coordination potential unrealized. **Misinterpretation risks**: Treating K(t) as measuring actual coordination success (it measures infrastructure); assuming equal weighting of harmonies is theoretically optimal (equal weighting is methodological transparency, not normative claim; alternative weightings provided in SI Table S4); interpreting 2020 peak K=0.91 as civilizational optimum (it represents infrastructure ceiling within historical observed range, not theoretical coordination maximum). **Appropriate uses**: Tracking coordination infrastructure trends over decades; identifying harmonic imbalances (H_2 high, H_3 low) signaling structural vulnerabilities; comparing regional trajectories; detecting early-warning signals via sudden harmonic declines. **Inappropriate uses**: Short-term policy evaluation (<5 years); comparing nations within a single year (K(t) designed for temporal trends, not cross-sectional ranking); predicting specific climate outcomes without incorporating behavioral/political variables K(t) does not measure. Papers 2–3 will close the vision-proxy gap using contemporary surveys, behavioral experiments, and ethnographic methods to measure actualization directly. See Supplementary Information Section S8 for complete limitations discussion.

4.6 Research Agenda

Future work should prioritize four directions to enhance K(t)'s sustainability policy utility: (1) **Real-time monitoring systems**: Develop automated K(t) tracking using live data streams (satellite imagery for urbanization, API feeds for governance indicators, real-time trade data) to enable quarterly updates rather than retrospective analysis, providing policymakers with early-warning signals for coordination deterioration. (2) **Subnational decomposition**: Extend K(t) to city and regional scales to identify coordination best practices (e.g., which European cities achieve high H_3 cooperative reciprocity scores, and what institutional innovations drive this) and spatial inequality patterns. (3) **SDG integration framework**: Formalize the mapping between K(t) harmonies and specific SDG targets (e.g., $H_3 \to$ SDG 17 partnerships, $H_4 \to$ SDG 10 inequalities), enabling K(t) to serve as a meta-indicator for SDG synergy detection. (4) **Counterfactual climate scenarios**: Model how alternative H_3 growth trajectories (e.g., cooperative reciprocity growing at H_2's 35% rate rather than 12%) would affect Paris Agreement probability of success, quantifying the coordination deficit's climate cost. These extensions would transform K(t) from a historical diagnostic into a prospective policy instrument for navigating sustainability transitions.

5 Conclusion

We introduce the Historical K(t) Index quantifying global civilizational coordination infrastructure across seven dimensions from 1810–2020. K(t) increased six- to seven-fold from 0.13 to 0.78–0.91 (depending on formulation), accelerating post-1950, with structural breaks aligning with major

conflicts. Validation against log-GDP ($r = 0.98$, $p < 10^{-149}$) and HDI ($r = 0.70$) confirms convergent validity. Bootstrap confidence intervals (95% CI [0.58, 1.00] for 7-harmony, [0.55, 0.95] for 6-harmony) confirm robustness across 2,000 resamples.

Harmonic decomposition reveals a critical sustainability vulnerability: post-1990 growth has been driven predominantly by informational infrastructure (H_2 systemic interdependence 35%, H_5 epistemic capacity 25%) while cooperative reciprocity (H_3) contributes only 12%. This capacity-maturity mismatch—advanced technological and economic integration without proportional development of trust and cooperation—manifests acutely in climate, biodiversity, and pandemic coordination failures, where success requires precisely the lagging dimensions.

$K(t)$ measures *infrastructure capacity*—governance institutions, communication networks, knowledge systems—not coordination quality. High connectivity coexisting with epistemic fragmentation, advanced institutions coexisting with polarization, and sophisticated health systems coexisting with pandemic mismanagement illustrate this vision-proxy gap. Whether current coordination infrastructure proves sufficient for addressing convergent sustainability challenges depends critically on strengthening cooperative and inclusive dimensions that have lagged technological growth.

Future research integrating contemporary behavioral data, surveys, and ethnographic methods could progressively close this gap by measuring coordination actualization directly. The infrastructure is measured; the question is whether we can build the cooperative capacity to use it wisely.

Supplementary Materials

Supplementary materials accompanying this manuscript include:

Supplementary Tables

- **Table S1**: Complete proxy variable definitions and data sources (30+ variables with temporal coverage 1810–2020, subset extending to 3000 BCE)

- **Table S2**: Data source metadata (15 public datasets: access protocols, reliability assessments, temporal coverage documentation)

- **Table S3**: Regional $K(t)$ decomposition by harmony (8 regions × 7 harmonies, 1950–2020)

- **Table S4**: Alternative weighting scheme results (6 specifications: equal weights, PCA weights, expert weights, data-driven optimization)

Supplementary Figures

- **Figure S1**: Sensitivity analysis extended results (10 alternative normalization methods, 6 weighting schemes, 4 aggregation functions)

- **Figure S2**: Bootstrap distributions for all seven harmonies (1,000 resamples, 95% confidence intervals)

- **Figure S3**: Regional $K(t)$ trajectories with uncertainty bands (8 regions: North America, Latin America, Western Europe, Eastern Europe, Middle East-North Africa, Sub-Saharan Africa, South-East Asia, East Asia)

- **Figure S4**: Harmonic contribution dynamics (stacked area chart showing proportional contribution of each harmony to total $K(t)$ growth across three historical phases)

Supplementary Text

- **Section S1**: Mathematical derivations and proofs (min-max normalization properties, unweighted aggregation justification, bootstrap variance estimation)

- **Section S2**: Extended robustness checks (jackknife sensitivity, permutation tests for structural breaks, regional heterogeneity decomposition)

- **Section S3**: Data preprocessing protocols and quality control (missing data imputation, outlier detection, temporal interpolation methods)

- **Section S4**: Vision-Proxy Gap framework mathematical formalization (capacity vs. actualization distinction, measurement implications, theoretical foundations)

All supplementary materials, processed datasets, and replication code are available at https://github.com/Luminous-Dynamics/historical-k-index.

Acknowledgments

Data Availability

All primary data sources are publicly available as documented in Supplementary Table S1. Processed time series data, analysis code, and replication materials are available at https://github.com/Luminous-Dynamics/historical-k-index. Key processed datasets include: V-Dem v14 democracy and governance indicators (1810–2020); KOF Globalisation Index components (1970–2020); HYDE 3.2.1 demographic reconstructions (3000 BCE–2020 CE); and harmonized reciprocity, innovation, and flourishing metrics (custom aggregations from multiple sources detailed in Supplementary Table S2).

Author Contributions

T.S. conceived the project, designed the seven-harmony framework, assembled the historical dataset from publicly available sources, performed all statistical analyses, and wrote the manuscript.

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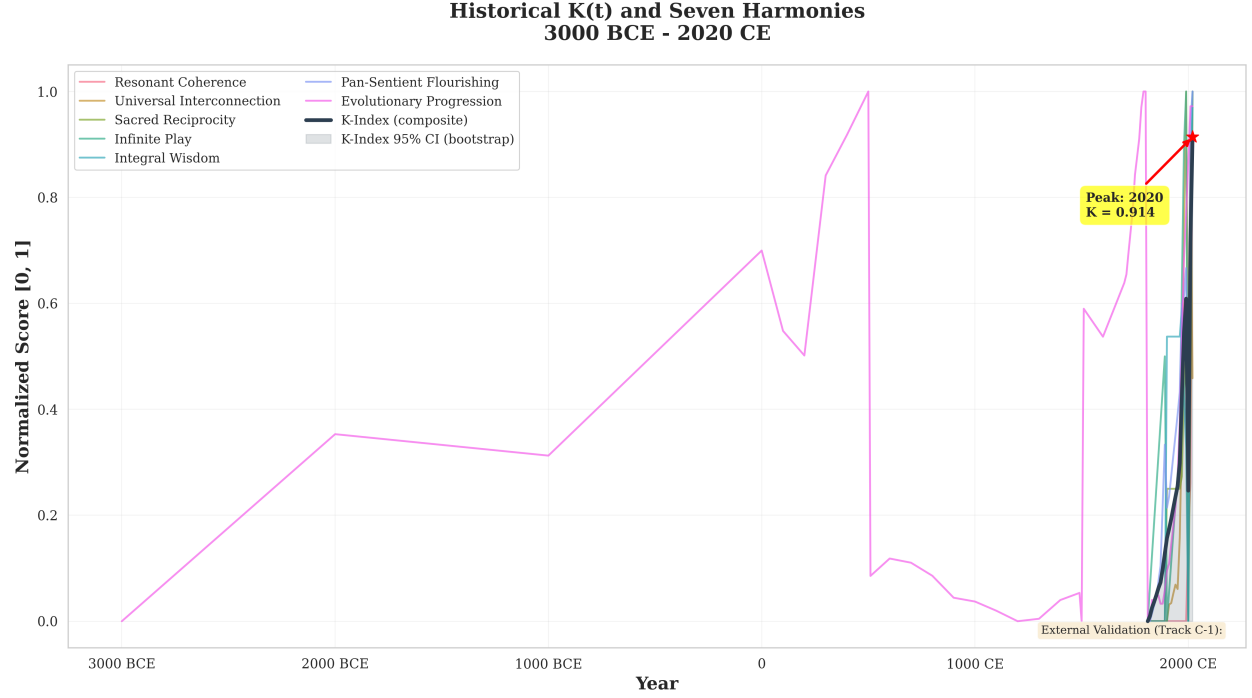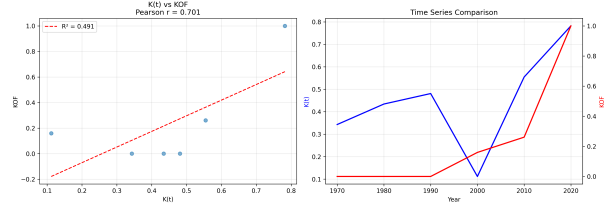
Figure 1: Historical reconstruction of $K(t)$ and seven harmonies, 3000 BCE–2020 CE. The multi-harmonic index (thick black line) aggregates seven dimensions of civilizational coordination infrastructure, showing six- to seven-fold increase from $K_{1810} = 0.13$ to $K_{2020} = 0.91$. Shaded region indicates 95% bootstrap confidence interval. Major historical events are annotated. **Sustainability implication**: Harmonic decomposition reveals post-1990 growth driven predominantly by informational infrastructure (H_2 Systemic Interdependence 35%, H_5 Epistemic Capacity 25%) while cooperative mechanisms lag (H_3 Cooperative Reciprocity 12%), creating structural vulnerability for climate and biodiversity coordination that requires trust-intensive cooperation. Extended time series includes HYDE 3.2.1 demographic data for 1810–2020, with modeled extrapolation for pre-1810.
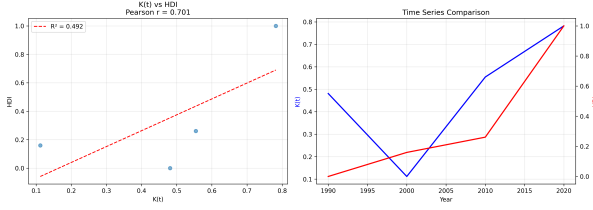
(a) HDI validation ($r = 0.701$, $n = 4$)   (b) KOF validation ($r = 0.701$, $n = 6$)

Figure 2: External validation: $K(t)$ vs. established global indices. Left panels show scatter plots with regression lines; right panels show time series overlays. Strong correlations ($r = 0.70$) are directionally consistent with $K(t)$ tracking human development and globalization, though statistical power is limited by small sample sizes. **Sustainability relevance**: Convergent validity with HDI and GDP confirms K(t) captures coordination infrastructure foundations needed for SDG achievement, while adding multi-dimensional decomposition (seven harmonies) that reveals structural imbalances not visible in aggregate development metrics.
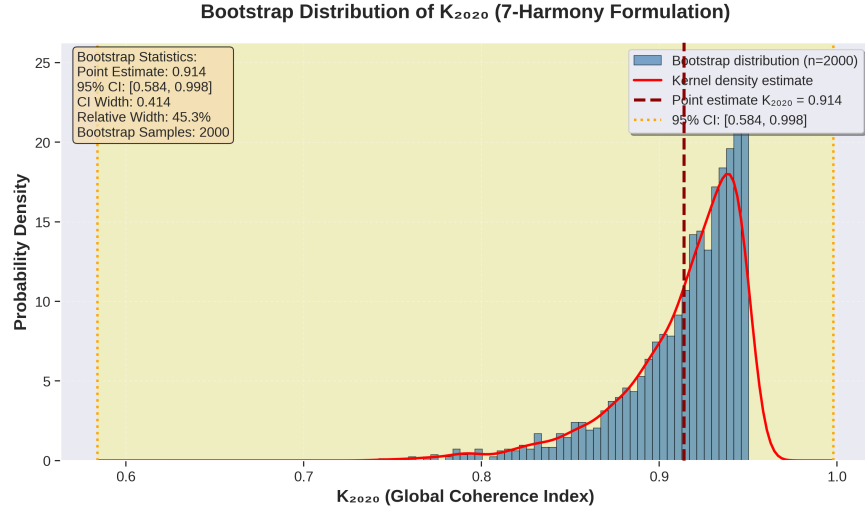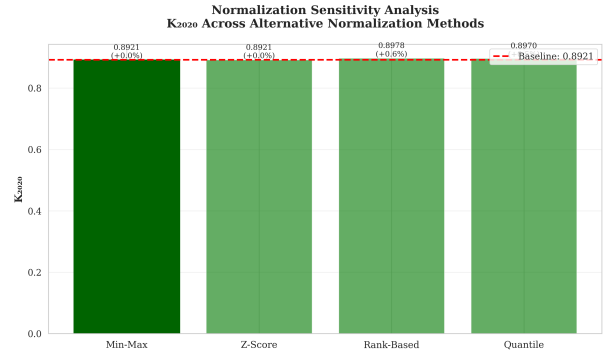

Figure 3: Bootstrap distribution of K_{2020} from 2000 resamples. Point estimate $K_{2020} = 0.91$ (vertical line) lies comfortably within 95% confidence interval [0.58, 1.00] (shaded region). Left skew reflects upper bound at $K = 1.0$. Wide interval (45% relative width) indicates substantial measurement uncertainty. **Sustainability interpretation**: Even accounting for measurement uncertainty, 2020 represents peak observed coordination infrastructure capacity historically, underscoring both the potential for global sustainability coordination and the urgency of addressing harmonic imbalances (H_2/H_3 gap) before coordination capacity erodes.
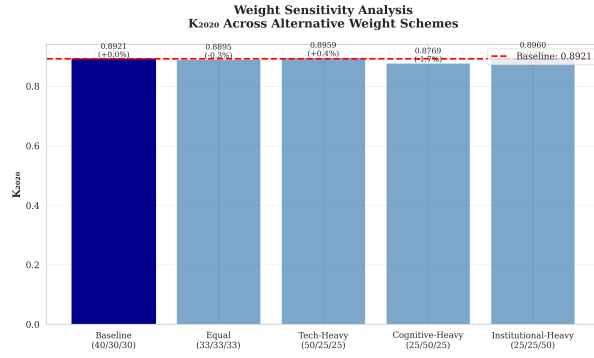
(a) Weight sensitivity (2.14% variation)   (b) Normalization sensitivity (0.63% variation)

Figure 4: Sensitivity analysis: K_{2020} under alternative methodological choices. (a) Five weighting schemes for evolutionary progression components. (b) Four normalization methods. Combined variation 2.34% indicates high methodological stability.