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Measuring Cognitive Capacity in Food Systems

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Abstract

Food systems transformation depends not only on finance, technology, and formal policy commitments, but also on whether countries can convert evidence into coordinated, implemented, and adaptive action. This paper develops the Food Systems Cognitive Capacity Index (FSCCI) as a policy diagnostic covering six system-level capacities: sensing and information, transparency and feedback, policy framing, collective action and coordination, administrative implementation, and anticipatory resilience. Using country-year data for the 2000–2023 period, the study constructs equal-weighted, principal component analysis (PCA)-weighted, and interdependence-adjusted versions of the FSCCI, alongside a Food Systems Cognitive Failure Index and a Food Systems Transformation Performance Index. The results show that cognitive capacity is measurable and policy-relevant, but its association with transformation performance depends on index construction and model specification. In the preferred one-year-lagged models, the equal-weighted estimate is positive but imprecise, whereas the PCA-weighted and interdependence-adjusted estimates remain positive and statistically significant. Additional controls preserve the positive direction of the association but reduce its precision. Regional and interaction analyses also reveal important contextual variation: the association is stronger in Latin America and the Caribbean, positively moderated by climate readiness, and negatively moderated by food-import dependence.

The policy implication is that food systems strategies should be accompanied by investments in the institutional capacities required for implementation. The FSCCI can help governments and development partners diagnose whether the binding constraint lies in weak data systems, limited feedback, fragmented coordination, poor implementation, or inadequate preparedness. It is therefore best used as a capacity-development tool rather than as a country-ranking instrument. Although the findings are associational rather than causal, they support a practical shift from measuring policy presence to assessing whether food systems can perceive problems, learn, coordinate, implement, and adapt.

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1. Introduction

Food systems transformation is increasingly treated as a governance and political economy challenge, as well as a production, technology, finance, and investment challenge (Fanzo et al. 2021; Ruben et al. 2021; Béné and Abdulai 2024). In this paper, “transformation” refers to a substantial and sustained change in food system outcomes and in the activities, relationships, and institutional arrangements that produce them. This is not synonymous with any short-term improvement in a single indicator. Following Ingram and Thornton (2022), it is useful to distinguish transformation of outcomes, adaptation of food system activities, and reassessment of the policies and signals that influence actors. Transformation is also not inherently beneficial: changes can generate gains in one domain and losses in another, and their durability must be assessed over an explicit time horizon.

Historical experience illustrates this distinction. The Green Revolution substantially increased cereal yields and reduced immediate production constraints in much of Asia, yet its longer-run effects also included uneven distributional gains, intensive input use, groundwater depletion, ecological stress, and continuing nutritional challenges (Pingali 2012). Such experience helps explain why contemporary food systems transformation is evaluated across multiple outcomes—healthy diets, food security, environmental sustainability, resilient livelihoods, equity, and accountability—rather than production alone. These objectives involve trade-offs, uncertainty, competing interests, and power relations. Here, institutions refer to formal and informal rules, norms, and decision procedures, while organizations refer to ministries, agencies, firms, research bodies, civil society organizations, and other collective actors operating within those rules.

The practical problem addressed by this paper is that relevant knowledge, policies, and resources often exist but remain fragmented across disciplines, sectors, organizations, and levels of government. Agricultural specialists may understand production constraints without fully incorporating nutrition or health; nutrition specialists may have limited engagement with production, trade, or environmental dynamics; and ministries may pursue formally legitimate but mutually inconsistent objectives. Food systems transformation therefore requires collective capacity to connect partial forms of knowledge, deliberate over trade-offs, align authority and incentives, and convert decisions into coordinated implementation. Existing scholarship identifies many elements of this problem, but usually examines monitoring, knowledge translation, policy capacity, adaptive governance, resilience, or coordination separately and in different substantive contexts.

This paper brings those elements together through the concept of food systems cognitive capacity. The term does not refer to the intelligence of individual policymakers, farmers, firms, or consumers. It refers to the collective governance capacity of actors, organizations, institutions, and knowledge infrastructures to move from data and experience to shared interpretation, decision, implementation, feedback, and adaptation. Cognitive capacity is therefore one enabling capacity among several; it cannot substitute for finance, infrastructure, technology, human resources, political authority, or material assets. Its proposed role is connective: it influences whether those other capacities are prioritized, combined, deployed, monitored, and revised in ways that advance agreed transformation goals.

The six domains used in the empirical framework are derived from five overlapping theoretical traditions. Knowledge systems research explains why evidence must be credible, salient, legitimate, and connected to action (Cash et al. 2003). Policy capacity research distinguishes analytical, operational, and political capabilities at individual, organizational, and system levels (Wu et al. 2015). Adaptive and transformative governance emphasize reflexivity, responsiveness, learning, coordination, and action under uncertainty (Folke et al. 2005; Termeer et al. 2015; Hölscher et al. 2019). Collective action literature highlights the rules, relationships, authority, and incentives needed to align actors, while resilience research emphasizes anticipation, feedback, diversity, and cross-scale adaptation. Together, these traditions motivate six domains: sensing and evidence; transparency, feedback, and learning; integrated problem framing and policy analysis; collective action and coordination; administrative and implementation capacity; and anticipatory and adaptive resilience.

This synthesis does not claim that monitoring, governance, knowledge translation, or policy capacity are new ideas. The contribution is instead to integrate them into a food-system-specific, country-comparative measurement framework and to treat their interaction as a potential systems property. The framework also clarifies the distinction between capacity and function. Capacity is the ability to perform; a function is the activity performed; and an outcome is the result produced. For example, sensing capacity enables the function of detecting changing conditions, but improved transformation outcomes depend on whether those signals are interpreted, coordinated, implemented, and used for learning.

The inverse condition is food systems cognitive failure: a system-level breakdown in the processes that connect knowledge to collective action. It can appear as fragmented or inaccessible data, weak public accountability, narrow problem definitions, policy silos, unclear mandates, limited implementation authority, lost institutional memory, delayed response, or inadequate preparation for chronic and acute stresses. Knowledge may exist somewhere in the system but fail to circulate, gain legitimacy, influence decisions, or survive staff and experts turnover. This is a problem of knowledge governance and collective action, not simply information scarcity. The analogy with translational research is useful: producing evidence is insufficient unless organizations can synthesize it, adapt it to policy problems, authorize action, implement responses, and learn from results.

The comparative question is therefore not whether one country or region is inherently more capable than another, but why similarly situated food systems differ in their ability to translate information, policy commitments, and investments into coordinated and sustained action. Are differences associated with sensing, feedback, problem framing, collective coordination, implementation, or anticipation? Can a common framework identify distinct capacity profiles rather than produce a decontextualized league table? These questions motivate the construction of the Food Systems Cognitive Capacity Index (FSCCI) and the Food Systems Cognitive Failure Index (FSCFI) using country-year data from the Food Systems Countdown Initiative (FSCI) for 2000–2023.

The study has three objectives. First, it develops a theoretically grounded and operational definition of food systems cognitive capacity. Second, it constructs equal-weighted, principal-component-weighted, and interdependence-adjusted versions of the FSCCI and examines their consistency. Third, it tests whether lagged cognitive capacity is associated with food systems transformation performance in panel models and robustness checks. The analysis is diagnostic and associational rather than a definitive causal design. Section 2 presents the framework; Sections 3 and 4 describe measurement and empirical strategy; Sections 5 and 6 report results and robustness checks; and Sections 7 and 8 discuss implications, limitations, and conclusions.

2. Conceptual Framework

The framework begins from the premise that food systems are simultaneously material, social, ecological, economic, and knowledge-to-action systems. They depend on signals about prices, production, nutrition, health, trade, ecosystems, conflict, climate, public administration, and household welfare. Those signals have no transformative effect by themselves. They must be generated, validated, synthesized, interpreted in relation to competing goals, communicated across organizational boundaries, connected to authority and resources, and translated into action.

Food systems cognitive capacity denotes the collective ability to perform this full sequence. A useful stylized cycle includes the following stages: data and experiential knowledge generation; validation and synthesis; interpretation and integrated problem framing; deliberation and choice; coordination and implementation; monitoring; and learning and policy revision. The sequence is analytical rather than strictly chronological. In practice, actors revisit earlier stages, contest problem definitions, update evidence, and adapt decisions as conditions change.

This is a form of distributed cognition. Perception, memory, interpretation, and decision-making are dispersed across people, organizations, technologies, records, routines, and institutional rules rather than located in a single decision-maker. The concept therefore includes scientific and administrative data, local and Indigenous knowledge, market intelligence, civil society experience, and organizational memory. A food system may be rich in information yet cognitively weak if these elements remain inaccessible, politically excluded, poorly integrated, or disconnected from implementation.

The empirical framework organizes this collective capacity into six domains. Sensing and evidence capacity involves detecting current conditions, structural trends, and emerging problems through statistics, surveillance, research, local knowledge, and early warning. Transparency, feedback, and learning capacity involves access to information, accountability, evaluation, institutional memory, and the use of results to revise action. Integrated problem framing and policy analysis capacity involves defining system boundaries, causes, affected groups, trade-offs, and feasible interventions rather than reducing a food system problem to one sector. Collective action and coordination capacity involves aligning mandates, authority, incentives, knowledge, and action across ministries, levels of government, firms, communities, and civil society. Administrative and implementation capacity involves budgeting, staffing, procurement, enforcement, service delivery, and continuity. Anticipatory and adaptive resilience involves scenario development, preparedness, prepositioned options, and the ability to adjust amid chronic uncertainty and acute shocks.

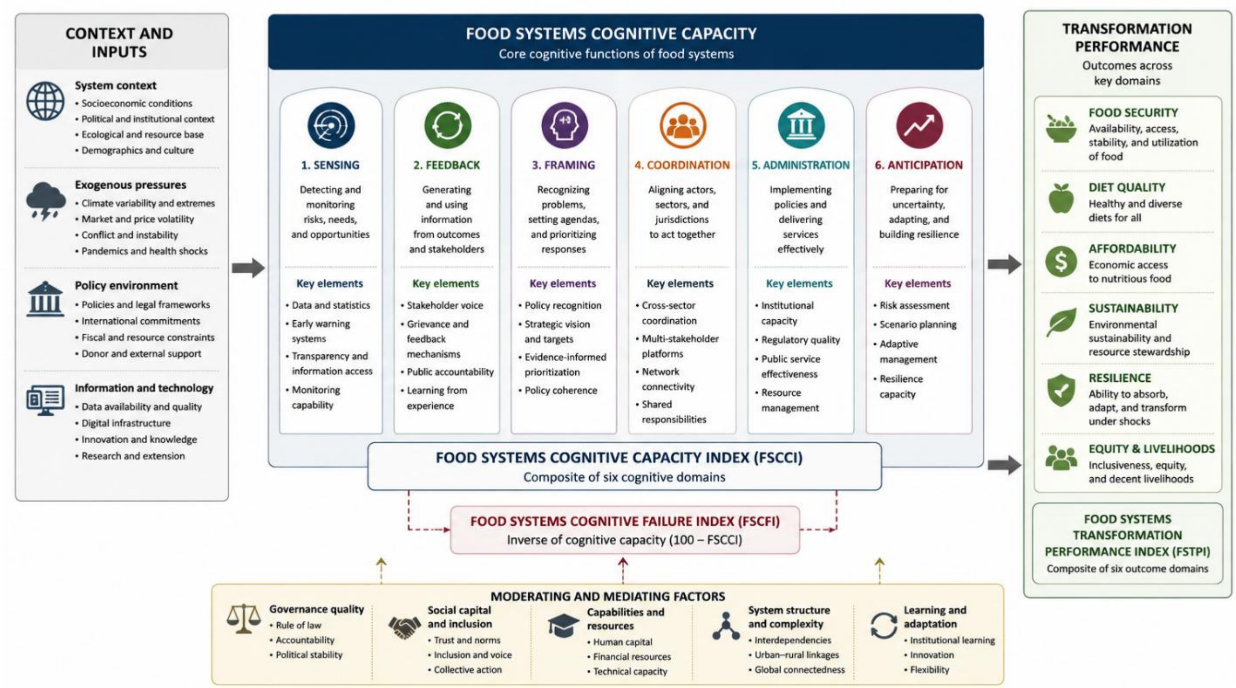
The domains are distinct but interdependent. Sensing identifies conditions, while anticipation uses evidence to consider future pathways and prepare options. Policy analysis frames the problem and alternatives; coordination organizes collective choice and action; implementation converts decisions into operations; and feedback generates learning that can alter each preceding stage. The relationships are expected to be recursive, complementary, and potentially nonlinear. A severe weakness in one domain may become a bottleneck, while an improvement in one capacity may yield little benefit until minimum capacities exist elsewhere. The interdependence-adjusted index used below is therefore an empirical approximation of interaction, not a definitive estimate of nonlinear causal mechanisms.

Figure 1.1 represents this recursive knowledge-to-action cycle. The six domains should not be read as a one-way production line. Arrows among the domains indicate repeated exchange, contestation, and learning, while the link to transformation performance is conditioned by finance, infrastructure, technology, political authority, market structure, inequality, conflict, geography, and ecological constraints. These contextual conditions can enable or block the conversion of cognitive capacity into improved outcomes.

The framework also locates policies within a broader process. Policies are not exogenous objects that simply appear and then operate. They emerge from knowledge production, problem framing, agenda setting, negotiation, authorization, and political choice. They subsequently require resourcing, coordination, implementation, monitoring, and revision. Accordingly, the relevant distinction is not only between policy absence and presence, but also between formal adoption and functional policy capacity. The latter asks whether institutions can translate commitments into sustained action and adapt when outcomes diverge from expectations.

This formulation helps unify concepts that might otherwise appear to compete with each other. Governance is the overarching process through which collective goals are set and pursued. Knowledge governance concerns how evidence is produced, validated, shared, contested, and used. Collective action and coordination concern actor alignment; administrative and implementation capacity concerns execution; feedback concerns learning; and anticipation concerns preparation for future conditions. Together, these are treated as domains of food systems cognitive capacity rather than as separate definitions of the construct.

Figure 1.1 Conceptual model of food systems cognitive capacity



Source: Author's conceptualization based on the literature cited in Section 2.

Note: The framework posits that stronger cognitive capacity improves transformation performance by enhancing the ability of food systems to sense, learn, coordinate, implement, and adapt. Cognitive failure represents weaknesses in these functions and constrains transformation. The six domains form a recursive knowledge-to-action system: sensing and evidence; integrated problem framing and policy analysis; collective action and coordination; administrative and implementation capacity; transparency, feedback, and learning; and anticipatory and adaptive resilience. Bidirectional arrows indicate interaction and iteration. Transformation performance is jointly shaped by these capacities and by material, financial, technological, political, socioeconomic, and ecological conditions.

The inverse concept, cognitive failure, refers to breakdowns in this connected system. Failure may occur because a condition is not detected, evidence is not trusted or shared, a problem is framed too narrowly, organizations cannot coordinate, decisions are not implemented, feedback is ignored, or preparedness does not lead to timely action. The framework extends beyond crisis management: it includes routine service delivery, chronic malnutrition, long-term environmental degradation, market and livelihood constraints, policy implementation, and short-, medium-, and long-term transformation challenges.

Treating cognitive capacity as a systems property does not imply that every domain must be maximized or that one institutional model fits all countries. Different political and administrative systems may perform these functions through different arrangements. The framework instead supplies a common diagnostic language for asking where knowledge-to-action processes are strong, where they break down, and which combinations of capacity and material investment are required in a given context.

The framework also imposes boundaries on interpretation. The available indicators are proxies for observable features of governance, information access, policy recognition, implementation, and resilience; they do not directly measure deliberative quality, leadership, informal knowledge, bureaucratic memory, political incentives, or the distribution of power. Moreover, higher cognitive capacity is neither necessary nor sufficient for every favorable outcome. Structural conditions and political choices remain consequential, and effective collective capacity can, in principle, be used to pursue goals that are contested or harmful.

The main empirical expectation is that higher lagged cognitive capacity will be positively associated with subsequent transformation performance, while higher cognitive failure will be negatively associated with performance. A secondary expectation is that the broad signal will persist across alternative weighting schemes and specifications that leave one domain out. These expectations concern coherence and diagnostic relevance, not causal identification.

Table 1.1 summarizes the theoretical logic. The empirical analysis then asks whether the six-domain construct is stable across alternative weighting approaches and whether within-country changes in lagged cognitive capacity are associated with subsequent transformation performance. Because the domains may reinforce one another, the analysis also examines an interdependence-adjusted specification while retaining the transparent equal-weighted index as the baseline.

Table 1.1 Theoretical domains of food systems cognitive capacity

Domain	Core system question	Theoretical basis and transformation role
Sensing and evidence	Can the system detect current conditions, structural trends, and emerging problems?	Knowledge systems, monitoring, and surveillance; creates an evidence base for diagnosis and action.
Transparency, feedback, and learning	Can evidence, implementation experience, and outcomes be scrutinized and used to revise action?	Accountability, organizational learning, and adaptive governance; supports correction and institutional memory.
Integrated problem framing and policy analysis	Can actors define interconnected causes, trade-offs, affected groups, and feasible options?	Policy capacity and systems analysis; reduces narrow sectoral responses.
Collective action and coordination	Can actors align authority, incentives, knowledge, and action across sectors and scales?	Collective-action and governance literature; enables joint decisions and implementation.
Administrative and implementation capacity	Can authorized decisions be financed, staffed, executed, enforced, and sustained?	Operational policy capacity and public administration; converts plans into delivery.
Anticipatory and adaptive resilience	Can the system prepare options for chronic uncertainty and acute shocks and adjust as conditions change?	Anticipatory governance and resilience; supports preparedness and adaptation.

Source: Author’s synthesis based on the literature cited in Section 2.

3. Data and Measures

The empirical analysis uses a country-year panel to assess whether food systems with stronger cognitive capacity also display stronger transformation performance. The measurement strategy separates explanatory capacities from realized outcomes and constructs three indexes: the FSCCI, FSCFI, and the Food Systems Transformation Performance Index (FSTPI). This separation reduces mechanical overlap between the explanatory and outcome measures.

Core food system indicators come from the FSCI, a global monitoring framework that tracks food system conditions and transformation toward 2030 (Food Systems Countdown Initiative 2025). The analytical period is 2000–2023. The FSCI draws on sources including FAOSTAT, the World Bank, ILO, V-Dem, UNICEF, AQUASTAT, FAOLEX, and EM-DAT and organizes indicators across diets and health; environment, natural resources, and production; livelihoods, poverty, and equity; governance; and resilience.

For the present study, selected FSCI governance, policy, information, and resilience indicators serve as observable proxies for system-level capacity. They capture features such as access to information, accountability, civil society participation, policy recognition, government effectiveness, food safety capacity, information infrastructure, and shock preparedness. They should not be interpreted as direct measures of cognition. The operational claim is narrower: taken together, the indicators approximate whether a food system possesses institutional and informational conditions that support knowledge-to-action processes.

3.1 Indicator Structure

Let i index countries, t index years, d index cognitive-capacity domains, and k index indicators within each domain. The raw value of indicator k in domain d for country i in year t is denoted as X_{itdk}

Table 3.1 maps the six theoretical domains to their operational functions and illustrative FSCI proxies. The labels are expanded for conceptual clarity, but the underlying indicators are unchanged: sensing and evidence; transparency, feedback, and learning; integrated problem framing and policy analysis; collective action and coordination; administrative and implementation capacity; and anticipatory and adaptive resilience.

Table 3.1 Operational mapping of FSCCI domains to illustrative FSCI indicators

Domain	Operational function	Illustrative FSCI proxies
Sensing and evidence	Detect and transmit food system conditions and risks.	Public access to information; mobile cellular subscriptions; food safety capacity.
Transparency, feedback, and learning	Enable scrutiny, accountability, correction, and institutional learning.	Open Budget Index; V-Dem accountability; civil society participation; public access to information.
Integrated problem framing and policy analysis	Recognize food system problems and policy commitments in integrated terms.	National food systems pathway; food environment policies; legal recognition of the right to food.
Collective action and coordination	Align stakeholders and knowledge across sectors, organizations, and levels.	Civil society participation; social capital; population share in cities participating in the Milan Urban Food Policy Pact.
Administrative and implementation capacity	Translate authorized priorities into operational action.	Government effectiveness; food safety capacity.
Anticipatory and adaptive resilience	Prepare for, absorb, and adjust to instability and shocks.	Dietary sourcing flexibility; food supply variability; food price volatility; disaster damages relative to GDP.

Source: Author's mapping based on Food Systems Countdown Initiative (2025) indicators.

3.2 Indicator Normalization

Because indicators are measured on different scales, all indicators are normalized before aggregation. For positively oriented indicators, where higher values indicate stronger cognitive capacity, min-max normalization is applied:

$$Z_{itdk} = \frac{X_{itdk} - \min(X_{dk})}{\max(X_{dk}) - \min(X_{dk})}.$$

For negatively oriented indicators, where higher raw values indicate weaker cognitive capacity, the normalized score is reversed:

$$Z_{itdk} = 1 - \frac{X_{itdk} - \min(X_{dk})}{\max(X_{dk}) - \min(X_{dk})},$$

where Z_{itdk} is the normalized indicator score. After normalization, all indicators are scaled so that higher values represent stronger cognitive capacity.

3.3 Domain Scores

Within each domain, normalized indicators are aggregated into a domain score. If domain d contains K_d indicators, the domain score is:

$$D_{itd} = \frac{1}{K_d} \sum_{k=1}^{K_d} Z_{itdk},$$

where D_{itd} represents the score of country I in year t f or cognitive domain d.

This step preserves the multidimensional structure of the index while allowing each domain to contribute to the overall FSCCI.

3.4 Food Systems Cognitive Capacity Index

The baseline FSCCI is constructed as the equal-weighted average of the six domain scores:

$$FSCCI_{it} = \frac{1}{6}\sum_{d=1}^{6} D_{itd}.$$

The baseline FSCCI is the equal-weighted average of the six domain scores. Equal weighting is used because it is transparent, reproducible, and consistent with the normative claim that each domain represents a necessary part of the knowledge-to-action system. It does not imply that the domains are empirically identical or equally consequential in every setting. Principal component analysis (PCA) weighting is used to test sensitivity to the covariance structure, and the interdependence-adjusted specification tests sensitivity to the assumed interaction structure. An expert-elicited weighting scheme could provide an additional validation exercise, but it would require a documented sampling frame, elicitation protocol, and uncertainty analysis rather than informal ranking by a small group.

3.5 Food Systems Cognitive Failure Index

The FSCFI is constructed as the inverse of the FSCCI:

$$\text{FSCFI}_{i,t-1} = 1 - \text{FSCCI}_{i,t-1}.$$

Higher values of $FSCFI_{it}$ indicate greater cognitive failure. This inverse index allows the same empirical framework to be interpreted from a failure perspective rather than a capacity perspective.

3.6 Alternative Index Specifications

To test whether the baseline index is sensitive to weighting assumptions, two alternative specifications are used.

First, a PCA-weighted index is constructed. Let w_d^{PCA} denote the PCA-derived weight assigned to domain d. The PCA-based cognitive-capacity index is:

$$FSCCI_{it}^{PCA} = \sum_{d=1}^{6} w_d^{PCA} D_{itd},$$

where:

$$\sum_{d=1}^{6} w_d^{PCA} = 1.$$

Second, an interdependence-adjusted index is constructed to reflect the fact that cognitive-capacity domains interact. Let w_d^{INT} denote the interdependence-adjusted weight for domain d. The interdependence-adjusted index is:

$$FSCCI_{it}^{INT} = \sum_{d=1}^{6} w_d^{INT} D_{itd},$$

where:

$$\sum_{d=1}^{6} w_d^{INT} = 1.$$

The interdependence-adjusted specification reflects the theoretical expectation that domains operate jointly. It should be interpreted as a sensitivity analysis rather than a direct estimate of nonlinear complementarity. For example, sensing without coordination may identify a problem but fail to generate action, while coordination without implementation authority may generate plans without operational change.

3.7 Food Systems Transformation Performance Index

The outcome variable is the FSTPI:

$FSTPI_{it}$.

The FSTPI measures transformation performance across food system outcomes, including food security, diet quality, affordability, sustainability, resilience, and equity and livelihoods. Consistent with the conceptual definition, a higher score indicates movement toward a more desirable multidimensional outcome profile, not proof of a permanent or universally beneficial transformation. Domain-level results are therefore reported alongside the aggregate index to reveal divergence and trade-offs.

If the FSTPI is also built as a composite index, its general form is

$$FSTPI_{it} = \sum_{m=1}^{M} \omega_m Y_{itm},$$

where the normalized outcome indicator and its assigned weight are defined separately from all FSCCI indicators. The baseline FSTPI uses transparent weighting, while sensitivity analysis should report whether rankings and regression estimates change under alternative domain weights. As with the FSCCI, statistical weights describe covariance rather than substantive importance, and any expert-weighted alternative would require a prespecified elicitation design.

3.8 Analytical Expectations

The measurement strategy implies three empirical expectations.

First, cognitive capacity should be positively associated with transformation performance:

$$\frac{\partial FSTPI_{it}}{\partial FSCCI_{it}} > 0.$$

Second, cognitive failure should be negatively associated with transformation performance:

$$\frac{\partial FSTPI_{it}}{\partial FSCFI_{it}} < 0.$$

Third, if the index captures a stable underlying construct, the alternative specifications should be strongly correlated with the baseline index:

$$corr\left(FSCCI_{it}, FSCCI_{it}^{PCA}\right) > 0 corr\left(FSCCI_{it}, FSCCI_{it}^{INT}\right) > 0.$$

These expectations are evaluated in the empirical strategy and results sections.

4. Empirical Strategy

The empirical strategy tests whether lagged food systems cognitive capacity is associated with subsequent transformation performance. It is designed as a diagnostic panel analysis rather than a causal treatment-effect design. The preferred specification uses country and year fixed effects and clusters standard errors by country. Two-way fixed-effects models can remove time-invariant country characteristics and common year shocks, but their interpretation depends on functional-form and exogeneity assumptions and should not be treated as design-based causal identification (Imai and Kim 2021). Country-clustered inference allows errors to be heteroskedastic and serially correlated within countries over time (Cameron and Miller 2015).

4.1 Baseline Panel Model

The primary model estimates the within-country association between the one-year-lagged FSCCI and the FSTPI:

$\mathrm{FSTPI}_{it} = \alpha + \beta\ \mathrm{FSCCI}_{i,t-1} + \mu_i + \lambda_t + \varepsilon_{it},$

where transformation performance is observed for country i in year t, cognitive capacity is measured in year t−1, country fixed effects absorb stable country characteristics, year fixed effects absorb common global shocks and trends, and the error term captures remaining variation.

The coefficient of interest is the estimated association between prior cognitive capacity and subsequent transformation performance. A positive and statistically significant coefficient is consistent with the paper's expectation, but it is not by itself evidence of a causal effect:

$\beta > 0.$

Country fixed effects account for time-invariant differences such as geography, long-run institutional history, and persistent structural features. Year fixed effects account for common shocks and trends. Standard errors are clustered at the country level. The identifying variation is therefore within-country change over time, not the cross-sectional difference between a high-ranked and low-ranked country.

4.2 Cognitive Failure Specification

Because cognitive failure is defined as the inverse of cognitive capacity, the same relationship can be estimated using the FSCFI:

$\mathrm{FSTPI}_{it} = \alpha + \theta\ \mathrm{FSCFI}_{i,t-1} + \mu_i + \lambda_t + \varepsilon_{it},$

where:

$FSCFI_{it} = 1 - FSCCI_{it}.$

The expected sign is negative:

$$\theta < 0$$

This specification provides an interpretive check. If cognitive capacity improves transformation performance, cognitive failure should be associated with weaker transformation performance.

4.3 Models with Control Variables

To examine whether the association is robust to observable country-year conditions, the model is extended to include a vector of controls:

$\mathrm{FSTPI}_{it} = \alpha + \beta\ \mathrm{FSCCI}_{i,t-1} + \gamma' X_{it} + \mu_i + \lambda_t + \varepsilon_{it},$

Where X_{it} is a vector of prespecified time-varying controls and γ is the corresponding coefficient vector. The controlled cognitive-failure counterpart is:

$\mathrm{FSTPI}_{it} = \alpha + \theta\ \mathrm{FSCFI}_{i,t-1} + \gamma' X_{it} + \mu_i + \lambda_t + \varepsilon_{it}.$

The control set must exclude any indicator used to construct the FSCCI, FSCFI, FSTPI, or the specific dependent variable in the model. Candidate controls available in the current export include agriculture's share of GDP, unemployment, and underemployment. Disaster damages and food price volatility are used as controls only in specifications where they are not components of either index. GDP per capita, conflict exposure, and climate vulnerability require external data merges.

Controls may reduce confounding by observed time-varying conditions, but they are included cautiously. Some variables may overlap conceptually with cognitive capacity, mediate its relationship with outcomes, or be jointly determined with transformation performance. The preferred interpretation is therefore whether the FSCCI coefficient remains directionally and substantively stable, not whether a controlled specification proves causality.

4.4 Alternative Index Specifications

To test whether the results depend on how cognitive capacity is weighted, the baseline model is re-estimated using the PCA-weighted index:

$$FSTPI_{it} = \alpha + \beta_{PCA} FSCCI_{i,t-1}^{PCA} + \mu_i + \lambda_t + \varepsilon_{it}$$

and the interdependence-adjusted index:

$FSTPI_{it} = \alpha + \beta_{INT} FSCCI_{i,t-1}{}^{INT} + \mu_i + \lambda_t + \varepsilon_{it}.$

The expected signs are:

$$\beta_{PCA} > 0 \beta_{INT} > 0$$

If these coefficients remain positive, the evidence suggests that the relationship is not an artifact of equal weighting.

The controlled counterparts are:

$$FSTPI_{it} = \alpha + \beta_{PCA} FSCCI_{i,t-1}^{PCA} + \gamma' X_{it} + \mu_i + \lambda_t + \varepsilon_{it}$$

$FSTPI_{it} = \alpha + \beta_{INT} FSCCI_{i,t-1}{}^{INT} + \gamma' X_{it} + \mu_i + \lambda_t + \varepsilon_{it}.$

4.5 Index Consistency Tests

Before interpreting the regression models, the analysis compares the alternative index specifications with the baseline FSCCI. The correlations are calculated as:

$\rho_{PCA} = corr\left(FSCCI_{it}, FSCCI_{it}^{PCA}\right) \rho_{INT} = corr\left(FSCCI_{it}, FSCCI_{it}^{INT}\right).$

High positive correlations would indicate that the alternative weighting strategies preserve the same broad empirical signal.

The analysis also compares the implied failure index with the capacity index:

$corr(FSCCI_{it}, FSCFI_{it}) < 0.$

Because $FSCFI_{it}$ is defined as 1-$FSCCI_{it}$, this relationship should be mechanically negative.

4.6 Leave-One-Domain-Out Robustness Tests

As reported in Table 4.1, the FSCCI is recalculated six times, each time excluding one domain. For excluded domain d, the leave-one-domain-out index is:

$FSCCI_{it}^{(-j)} = \frac{1}{5} \sum_{\substack{d=1 \\ d \neq j}}^{6} D_{itd}.$

The corresponding regression is:

$FSTPI_{it} = \alpha + \beta_{-d} FSCCI_{i,t-1}{}^{(-d)} + \mu_i + \lambda_t + \varepsilon_{it}.$

If β_(−d) remains positive across all six exclusions, the main result is not dependent on a single cognitive-capacity domain. The controlled counterpart is:

$FSTPI_{it} = \alpha + \beta_{-d} FSCCI_{i,t-1}{}^{(-d)} + \gamma' X_{it} + \mu_i + \lambda_t + \varepsilon_{it}.$

Table 4.1 Robustness logic for leave-one-domain-out tests

Test	Purpose	Interpretation
Exclude sensing and evidence	Checks whether results depend only on detection and evidence capacity	A positive coefficient supports robustness
Exclude feedback and learning	Checks whether results depend only on transparency, monitoring, and learning	A positive coefficient supports robustness
Exclude problem framing and policy analysis	Checks whether results depend only on integrated diagnosis and policy analysis	A positive coefficient supports robustness
Exclude collective action and coordination	Checks whether results depend only on actor alignment	A positive coefficient supports robustness
Exclude administrative and implementation capacity	Checks whether results depend only on execution capacity	A positive coefficient supports robustness
Exclude anticipatory and adaptive resilience	Checks whether results depend only on preparedness and adaptation	A positive coefficient supports robustness

Source: Author's methodological framework.

4.7 Missing-Data Robustness

Composite indexes can be sensitive to missing data. To test this, the analysis applies alternative missing-data thresholds. Let M_{itd} represent the share of available indicators in domain d for country i in year t. A domain score is retained only if:

$$M_{itd} \geq \tau,$$

where τ is the minimum data-availability threshold.

The analysis then re-estimates the baseline model under alternative values of τ:

$$\mathrm{FSTPI}_{it}^{(\tau)} = \alpha + \beta_\tau \, \mathrm{FSCCI}_{i,t-1}^{(\tau)} + \mu_i + \lambda_t + \varepsilon_{it}.$$

If the sign and approximate magnitude of the coefficient remain stable, the results are less likely to be driven by a particular missing-data rule.

The controlled missing-data-threshold specification is:

$$\mathrm{FSTPI}_{it} = \alpha + \beta_\tau \, \mathrm{FSCCI}_{i,t-1}^{(\tau)} + \gamma' X_{it} + \mu_i + \lambda_t + \varepsilon_{it}.$$

4.8 Regional Heterogeneity

Food systems operate in different institutional, ecological, and economic contexts. To test whether the association varies across regions, the analysis estimates region-specific models:

$$\mathrm{FSTPI}_{it,r} = \alpha_r + \beta_r \, \mathrm{FSCCI}_{i,t-1} + \mu_i + \lambda_t + \varepsilon_{it,r},$$

where r indexes region.

This specification evaluates whether the FSCCI–FSTPI association is broadly visible across regions or concentrated in particular regional contexts.

For region r, the controlled specification is:

$$\mathrm{FSTPI}_{it,r} = \alpha_r + \beta_r \, \mathrm{FSCCI}_{i,t-1} + \gamma' X_{it} + \mu_i + \lambda_t + \varepsilon_{it,r}.$$

4.9 Outcome-Specific Models

The FSTPI is a summary measure of transformation performance. To test whether cognitive capacity is associated with specific food system outcomes, the analysis estimates models for individual outcome indicators:

$$O_{mit} = \alpha_m + \beta_m \mathrm{FSCCI}_{\mathrm{i,t\text{-}1}} + \mu_i + \lambda_t + \varepsilon_{mit},$$

where O_{mit} is transformation outcome m for country i in year t. The controlled outcome-specific specification is:

$$O_{mit} = \alpha_m + \beta_m \mathrm{FSCCI}_{\mathrm{i,t\text{-}1}} + \gamma' X_{it} + \mu_i + \lambda_t + \varepsilon_{mit}.$$

For outcome-specific models, X_{it} must also exclude variables used to construct outcome m. This prevents a control from mechanically portioning out part of the dependent variable.

4.10 Interpretation

The coefficient should be interpreted as an adjusted within-country association between lagged cognitive capacity and subsequent transformation performance, net of common year shocks. Fixed effects and temporal ordering strengthen the diagnostic interpretation but do not eliminate time-varying omitted variables, reverse causality over longer horizons, policy endogeneity, or measurement error.

All headline coefficients in Sections 5–8 use the one-year-lagged, domain-weighted specification defined above. Correlations among index versions use the common complete sample across all three indexes. Earlier unversioned narrative values are retained only in the reproducibility audit and are not treated as current results.

The purpose is therefore to test coherence, temporal ordering, and robustness rather than definitive causation. Stronger causal claims would require a plausibly exogenous reform, a well-supported comparison group, and designs such as event studies, difference-in-differences, instrumental variables, or synthetic controls.

5. Results

This section presents the empirical results on the relationship between food systems cognitive capacity and transformation performance. It first assesses whether alternative FSCCI specifications preserve a common signal, then describes cross-country, regional, and temporal patterns, reports the fixed-effects association, and examines alternative weighting and outcome-specific results.

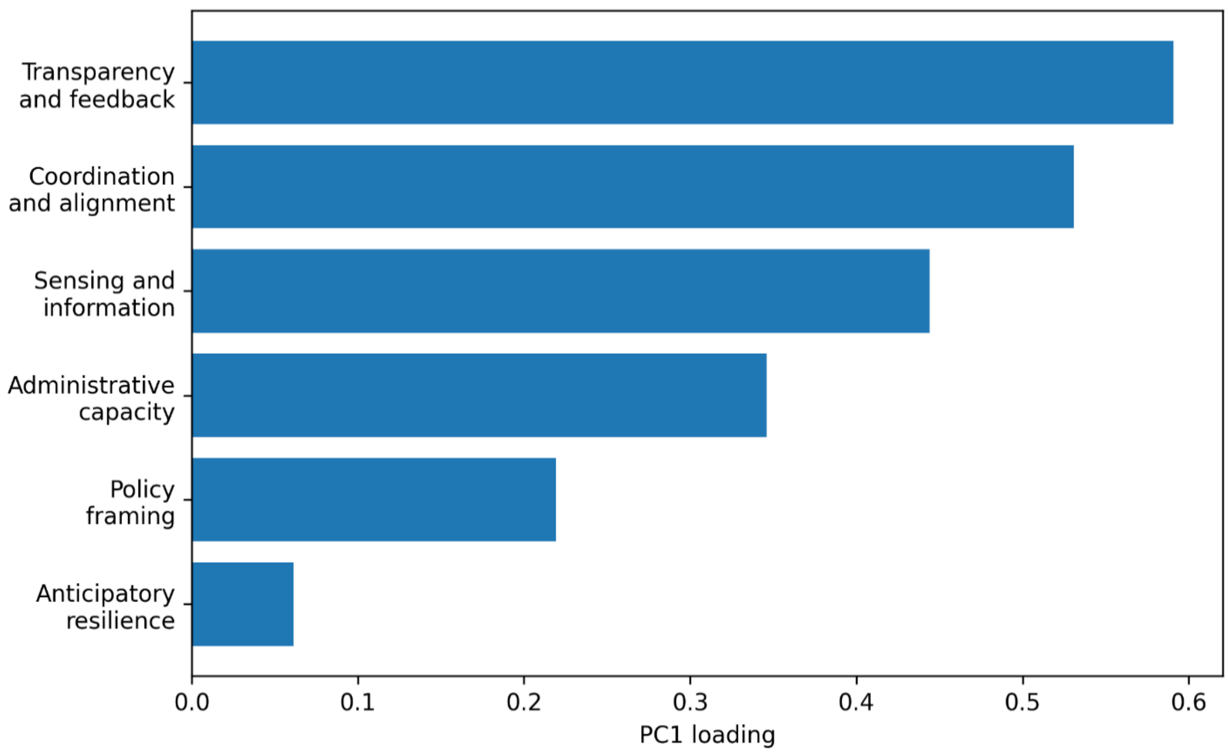
Taken together, the results show that food systems cognitive capacity is measurable and that its association with transformation performance is directionally positive but sensitive to index construction and temporal specification. The equal-weighted lagged coefficient is imprecisely estimated, whereas the PCA and interdependence-adjusted lagged coefficients are positive and statistically significant. The evidence is associational rather than causal, but it is consistent with food systems scholarship emphasizing monitoring, governance, coordination, adaptive learning, and institutional capacity (Fanzo et al. 2021; Ruben et al. 2021; Béné and Abdulai 2024).

5.1 Validation of the Cognitive-Capacity Construct

The first question is whether the FSCCI behaves as a coherent composite rather than a mechanical aggregation of unrelated indicators. Composite-index validation requires several forms of evidence. Agreement across weighting schemes provides evidence of convergent stability, but it does not alone establish discriminant validity, causal meaning, or the correctness of the six-domain theory.

The principal component analysis provides an initial validation of the cognitive-capacity construct (Figure 5.1). The first component loads positively across the major cognitive domains, although the strength of the loadings differs. Transparency and feedback receive the strongest loading, followed by collective action and coordination, sensing and evidence, administrative and implementation capacity, integrated problem framing and policy analysis, and anticipatory and adaptive resilience. This ordering is substantively meaningful. It suggests that the common empirical signal in the cognitive-capacity construct is especially associated with transparency, accountability, information flow, and coordination. These are precisely the capacities emphasized in the literature on food systems governance, where transformation is understood to require monitoring, feedback, cross-sectoral coordination, and institutional learning (Fanzo et al. 2021; Ruben et al. 2021).

Figure 5.1 PCA loadings for the cognitive capacity construct

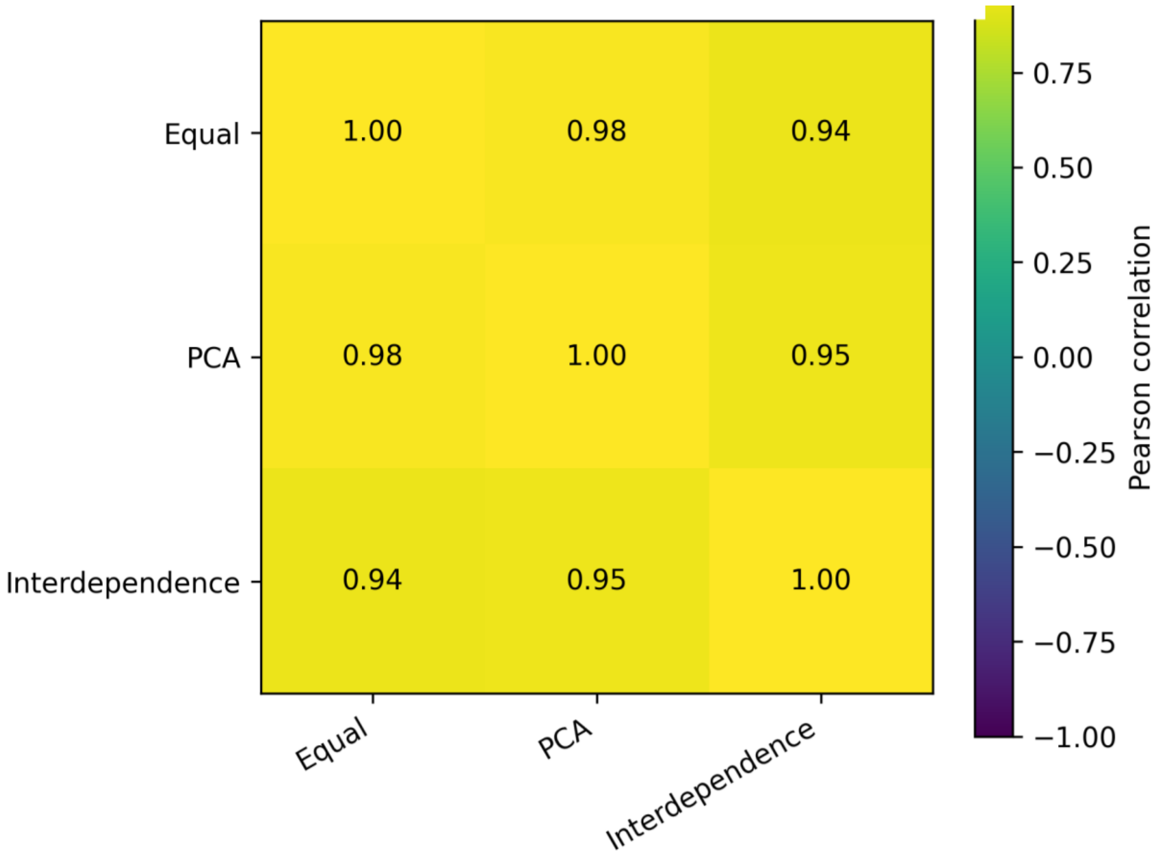


Source: Author's calculations using Food Systems Countdown Initiative (2025) data.

Note: The figure reports the first principal component loadings for the six cognitive capacity domains. Higher loadings indicate domains that contribute more strongly to the shared empirical signal captured by the PCA-weighted FSCCI. Transparency and feedback, coordination and alignment, and sensing and information show the strongest loadings, suggesting that the core empirical signal of cognitive capacity is closely linked to information flow, accountability, and coordination.

The correlation analysis provides evidence of convergent stability. On the common complete sample of 4,105 country-year observations from 187 countries, the equal-weighted FSCCI is correlated at 0.984 with the PCA-weighted version and at 0.942 with the interdependence-adjusted version (Figure 5.2). These values indicate that the broad country-year pattern is not generated solely by one weighting choice. They should not, however, be interpreted as definitive construct validation, because all three indexes draw on overlapping indicators.

Figure 5.2 Correlations among cognitive capacity index specifications

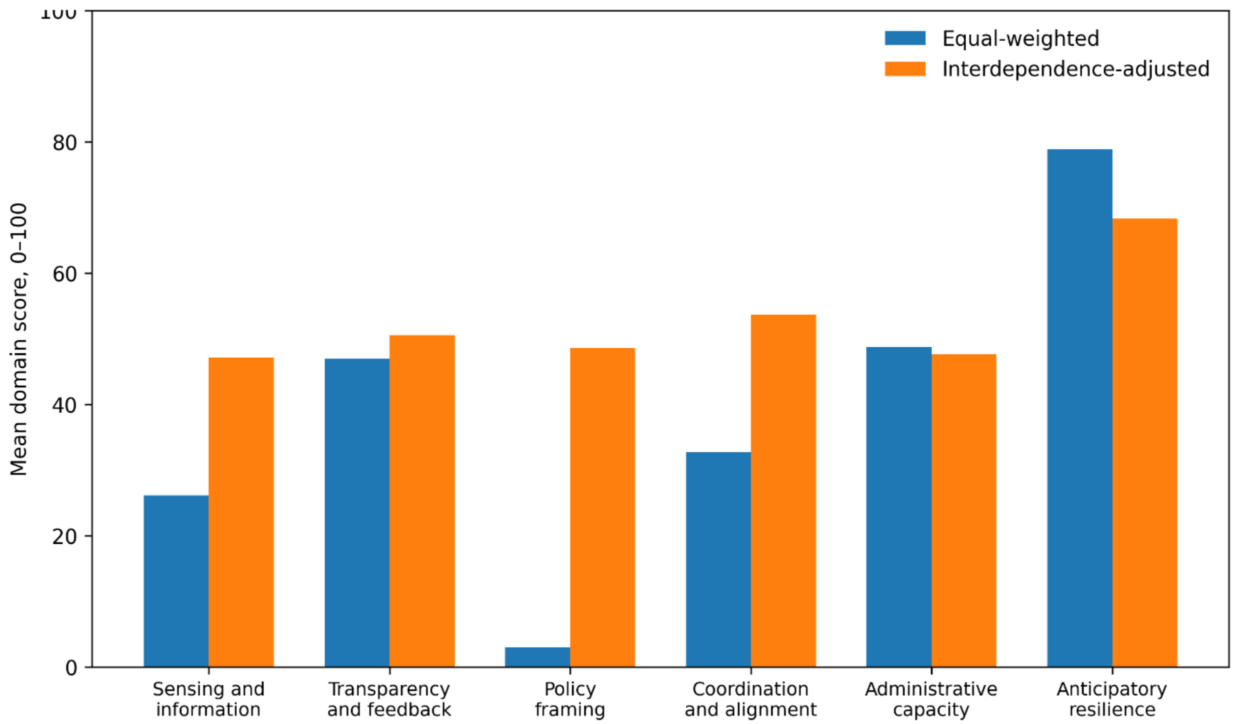


Source: Author's calculations using Food Systems Countdown Initiative (2025) data.

Note: The heatmap shows pairwise correlations among the equal-weighted, PCA-weighted, and interdependence-adjusted FSCCI specifications. The high positive correlations indicate that the alternative indexes capture a common underlying construct. This supports the use of the equal-weighted FSCCI as the baseline measure while also justifying the use of PCA-weighted and interdependence-adjusted versions as robustness specifications.

The comparison between equal-weighted and interdependence-adjusted domain scores is also informative (Figure 5.3). Under the interdependence-adjusted approach, domains such as sensing and evidence, integrated problem framing and policy analysis, and coordination receive higher adjusted scores relative to their equal-weighted levels, while anticipatory and adaptive resilience remains high but somewhat lower after adjustment. This suggests that the interdependence correction changes the profile of the index in ways that are conceptually plausible. Cognitive capacity is not simply the sum of separate capacities. Sensing, framing, coordination, feedback, implementation, and anticipation reinforce one another. A food system may detect emerging problems, but unless information is transmitted, interpreted, coordinated, and acted upon, the system may still fail to transform.

Figure 5.3 Cognitive capacity domains before and after interdependence adjustment



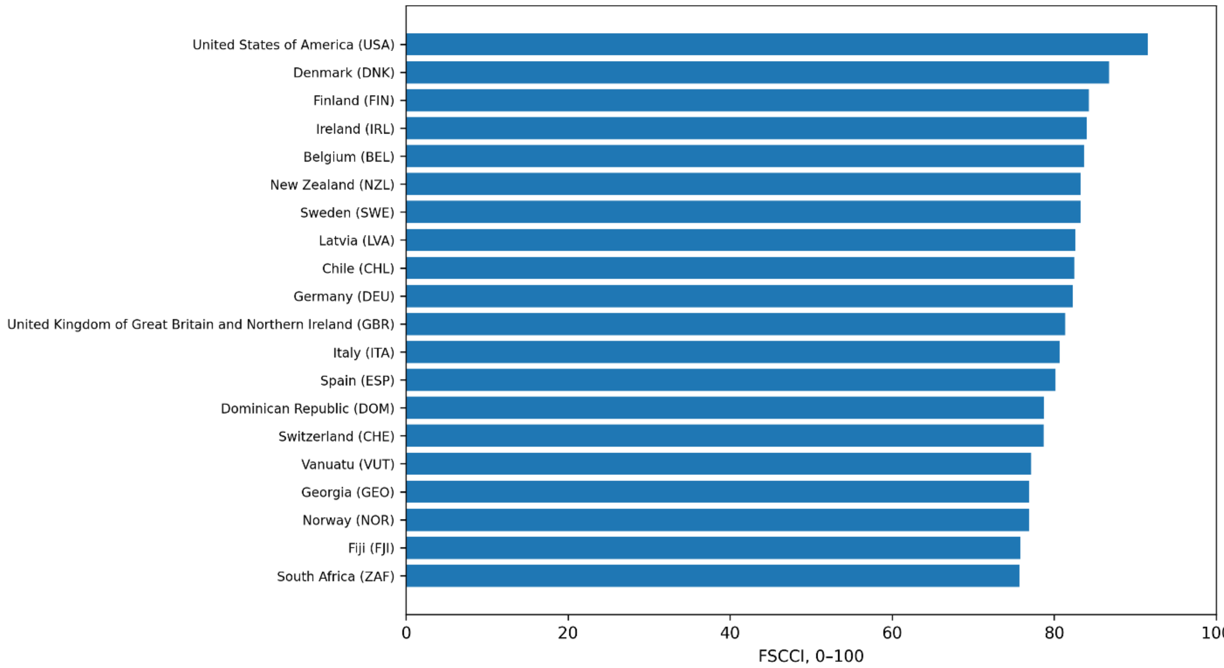
Source: Author's calculations using Food Systems Countdown Initiative (2025) data.

Note: The figure compares average domain scores under the equal-weighted and interdependence-adjusted approaches. The adjustment highlights the extent to which domains may reinforce one another rather than operate independently. The figure supports the theoretical claim that cognitive capacity is a systems property shaped by interactions among information, feedback, coordination, implementation, and anticipation.

5.2 Descriptive Patterns in Cognitive Capacity and Cognitive Failure

The 2023 rankings reveal substantial cross-country variation, but they are diagnostic profiles rather than rankings of national intelligence or overall policy quality. The top group includes countries from several regions, while South Africa is the only sub-Saharan African country appearing in the reported top 20. Fiji, Vanuatu, and other Pacific cases warrant domain-level interpretation because climate exposure and preparedness can raise anticipatory resilience scores even when other capacities differ. The presence of small states near the top does not by itself establish a small-country advantage; population, geographic scale, climate readiness, income, and data coverage are potential correlates that require separate analysis. Figure 5.4 shows the 20 countries and economies with the highest FSCCI scores in 2023.

Figure 5.4 Top 20 countries and economies by FSCCI 2023

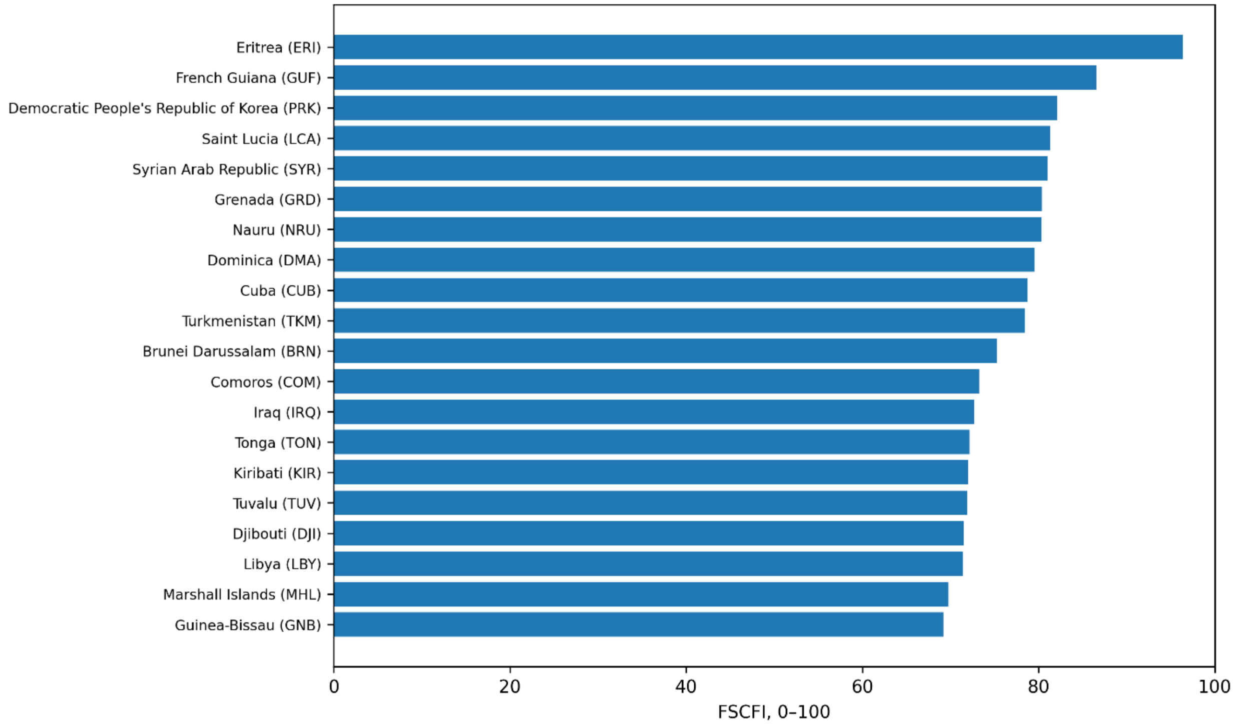


Source: Author's calculations using Food Systems Countdown Initiative (2025) data.

Note: The ranking is intended to identify contrasting capacity profiles, not to provide a context-free league table.

The inverse FSCFI also varies widely. Some high-failure cases—including resource-rich or import-dependent economies—may appear puzzling when judged only by current food availability. This is not necessarily a contradiction: the index measures institutional and knowledge-to-action capacities rather than food self-sufficiency or present caloric adequacy. Nevertheless, cases such as Brunei Darussalam and Turkmenistan raise a valid measurement question: information transparency, policy proxies, and uneven indicator coverage may contribute to high measured failure scores even where trade finances food access. Country narratives and sensitivity analysis using import dependence are therefore necessary before substantive interpretation. Figure 5.5 displays the countries and economies with the highest FSCFI scores in 2023.

Figure 5.5 Highest cognitive failure scores, 2023

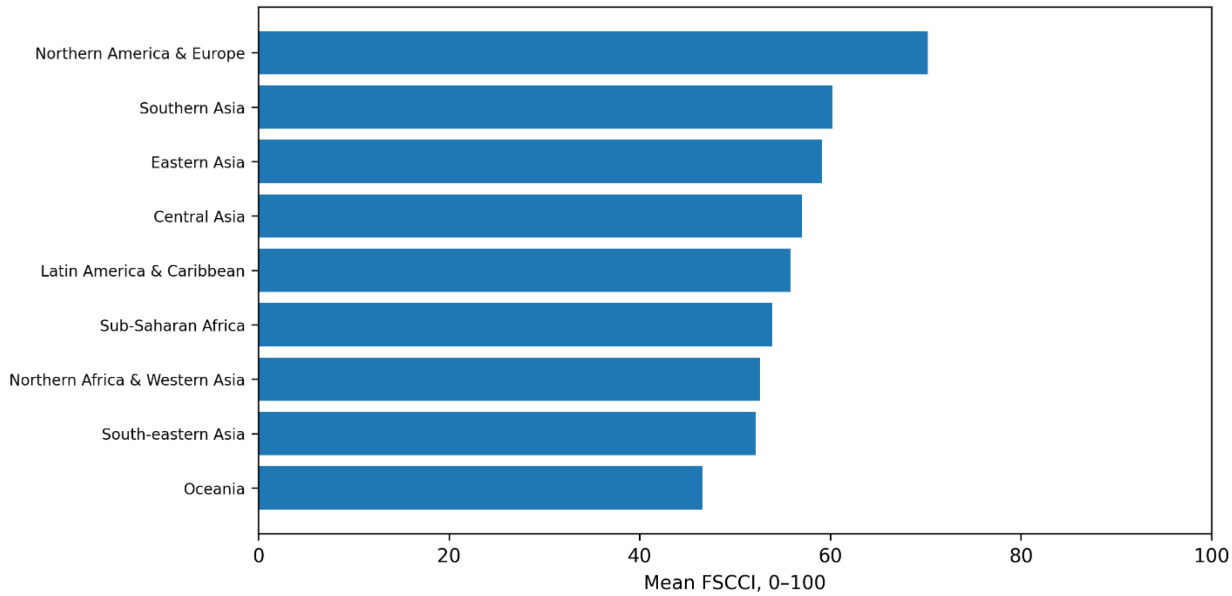


Source: Author's calculations using Food Systems Countdown Initiative (2025) data.

Note: High FSCFI values identify potential breakdowns in sensing, transparency, coordination, implementation, or anticipation. They should be interpreted alongside food-import dependence, income, data coverage, and country context.

Regional means reveal broad institutional and informational differences but should not be treated as deterministic rankings. Regional samples also differ in size and coverage. For example, a "top five" display for Central Asia may include the region's complete observed sample, whereas the same display is highly selective in larger regions. Figures and tables should therefore report the number of observed countries and the data-coverage rule used. Figure 5.6 summarizes mean FSCCI scores across regions in 2023.

Figure 5.6 Regional mean FSCCI, 2023

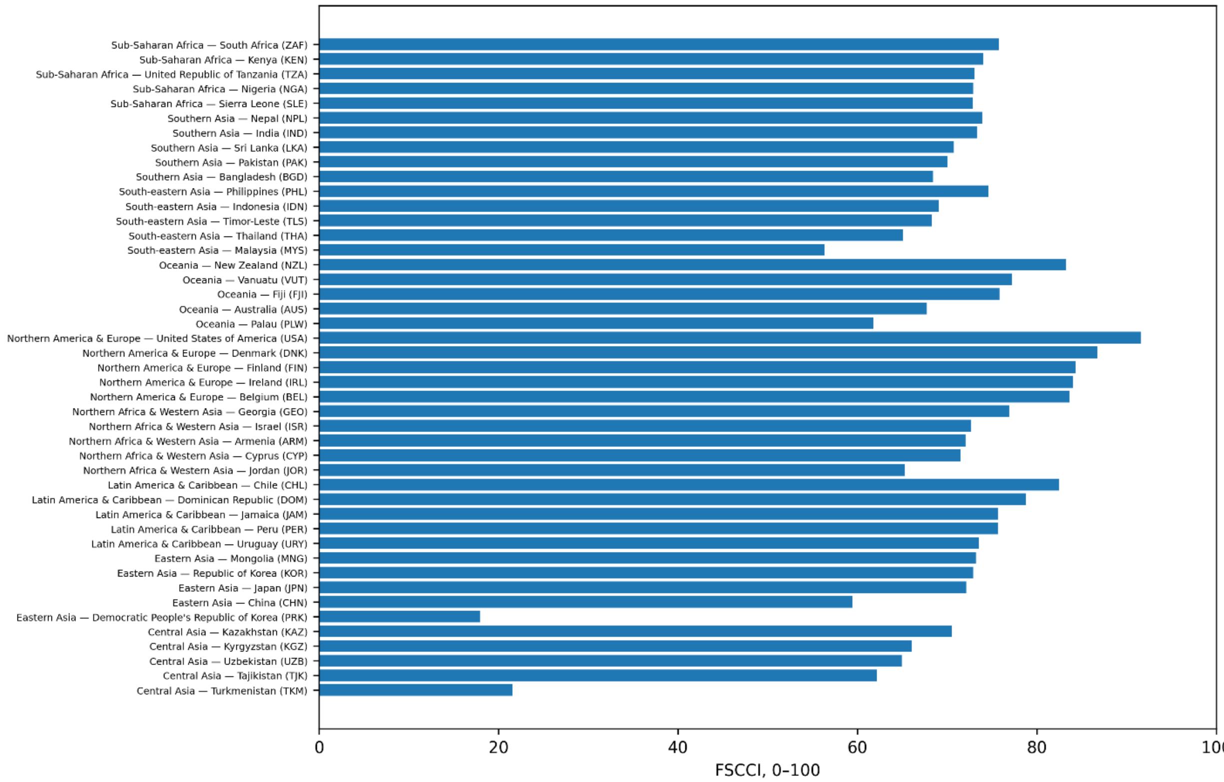


Source: Author's calculations using Food Systems Countdown Initiative (2025) data.

Note: Regional means are accompanied by the number of observed countries and should be interpreted as descriptive summaries rather than estimates of regional transformation potential.

Within-region rankings show that comparatively stronger profiles exist in diverse contexts, but the denominator matters. The Central Asia panel contains only five observed countries, so all may appear in a top-five chart. In South Asia, Bhutan's absence from the reported top group should be checked against its score and indicator coverage rather than interpreted substantively without verification. These examples reinforce the need to present sample size, coverage, and domain profiles with every ranking. Figure 5.7 compares the highest-scoring observed countries and economies within each region.

Figure 5.7 Top countries and economies within each region, FSCCI 2023



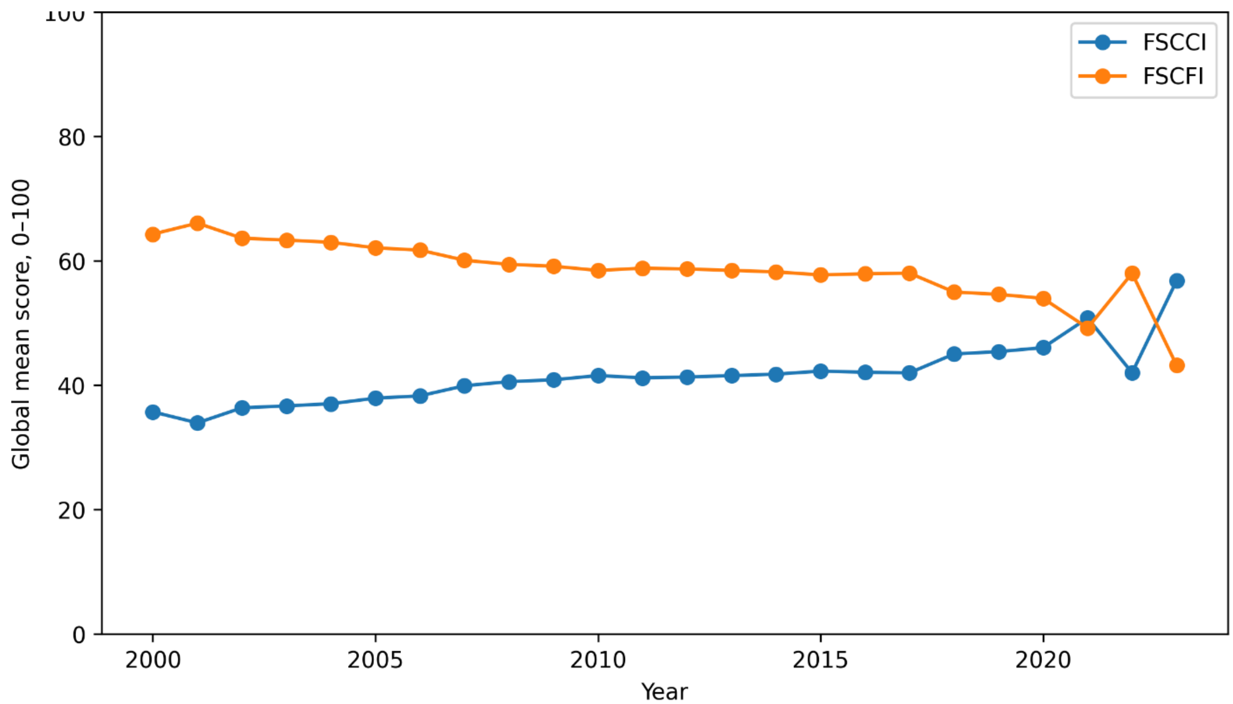
Source: Author's calculations using Food Systems Countdown Initiative (2025) data.

Note: Each panel reports the regional sample size and available-data rule; panels with five or fewer observed countries represent the complete regional sample.

5.3 Global Trends in Cognitive Capacity, Cognitive Failure, and Transformation Performance

The temporal results show that global mean cognitive capacity generally increased between 2000 and 2023, while cognitive failure generally declined (Figure 5.8). This pattern is consistent with the expansion of food system monitoring, governance attention, information systems, and resilience-oriented policy discussions over the past two decades. The trend is not perfectly smooth, however. There are visible fluctuations in the most recent years, suggesting that global shocks, data availability, or changing food system conditions may affect measured cognitive capacity and cognitive failure.

Figure 5.8 Global trends in food system cognitive capacity and cognitive failure, 2000–2023

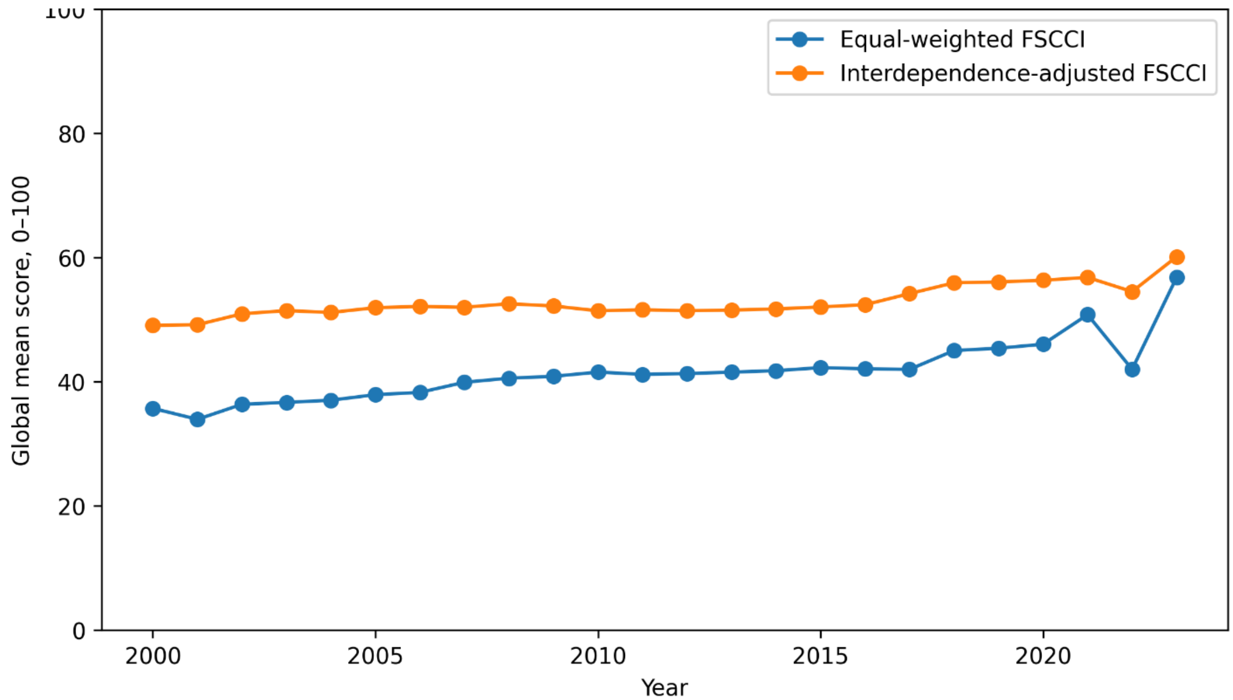


Source: Author's calculations using Food Systems Countdown Initiative (2025) data, 2000–2023.

Note: The figure compares the global mean FSCCI and FSCFI over time. Cognitive capacity generally rises, while cognitive failure generally declines, indicating gradual improvement in the global knowledge-to-action and adaptive capacities of food systems. The fluctuations in recent years suggest that cognitive capacity remains sensitive to shocks, measurement coverage, and changing institutional conditions.

The comparison of equal-weighted and interdependence-adjusted FSCCI trends shows that both indexes move in a similar direction over time, although the interdependence-adjusted specification remains consistently higher (Figure 5.9). This is consistent with the idea that domains of cognitive capacity are mutually reinforcing. When cognitive functions interact positively, the overall system-level capacity may be greater than what is captured by a simple equal-weighted average. At the same time, the similarity in trends reinforces the earlier validation result: the main empirical pattern is not dependent on one weighting approach.

Figure 5.9 Global cognitive capacity trends under alternative index constructions, 2000–2023

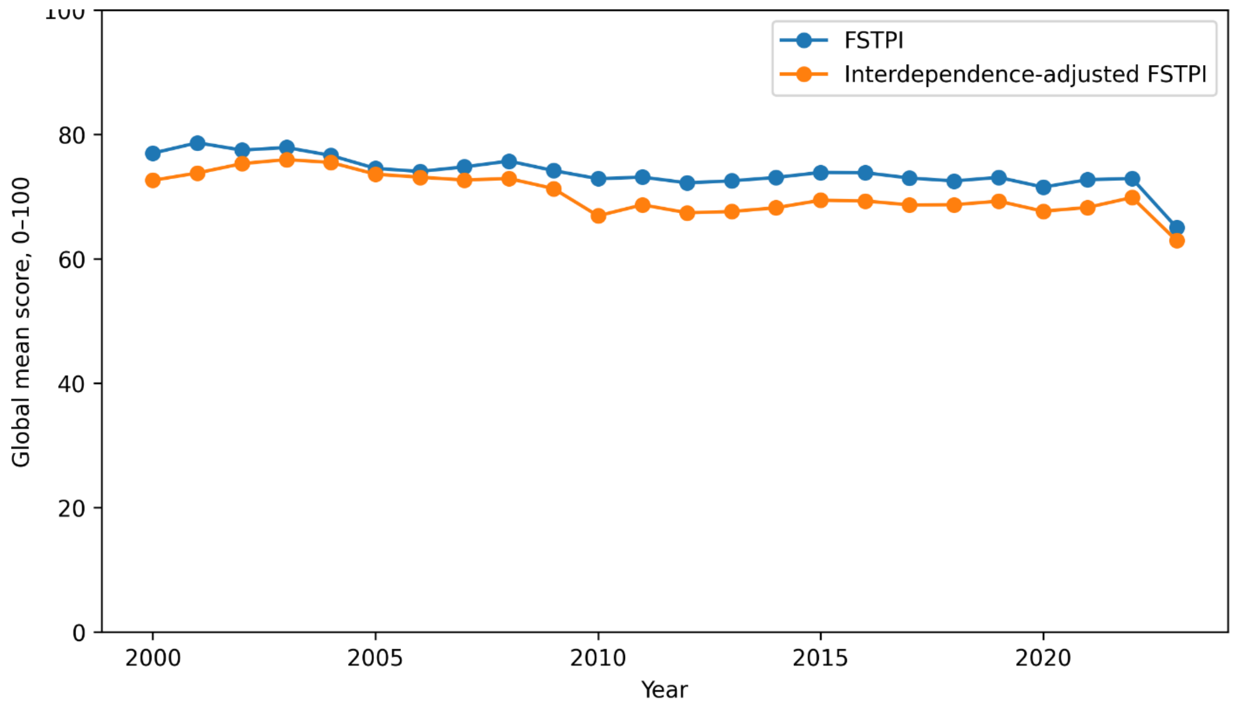


Source: Author's calculations using Food Systems Countdown Initiative (2025) data, 2000–2023.

Note: The figure compares global mean FSCCI scores under equal-weighted and interdependence-adjusted constructions. Both specifications show a broadly similar upward trajectory, while the interdependence-adjusted index remains higher. This supports the argument that cognitive domains interact and that the overall signal is robust to alternative index construction methods.

Transformation performance follows a different pattern (Figure 5.10). The global mean FSTPI does not show the same steady improvement as cognitive capacity. Instead, it remains relatively high in the early years, declines modestly over time, and shows a sharper reduction toward the end of the period. This divergence is analytically important. It suggests that improvements in cognitive capacity do not automatically translate into immediate or uniform gains in transformation outcomes. Food systems transformation is shaped by many structural forces, including income, conflict, climate stress, market disruptions, ecological constraints, and policy implementation quality. Cognitive capacity may be an enabling condition, but it is not the only determinant of outcomes.

Figure 5.10 Global trends in food systems transformation performance, 2000–2023

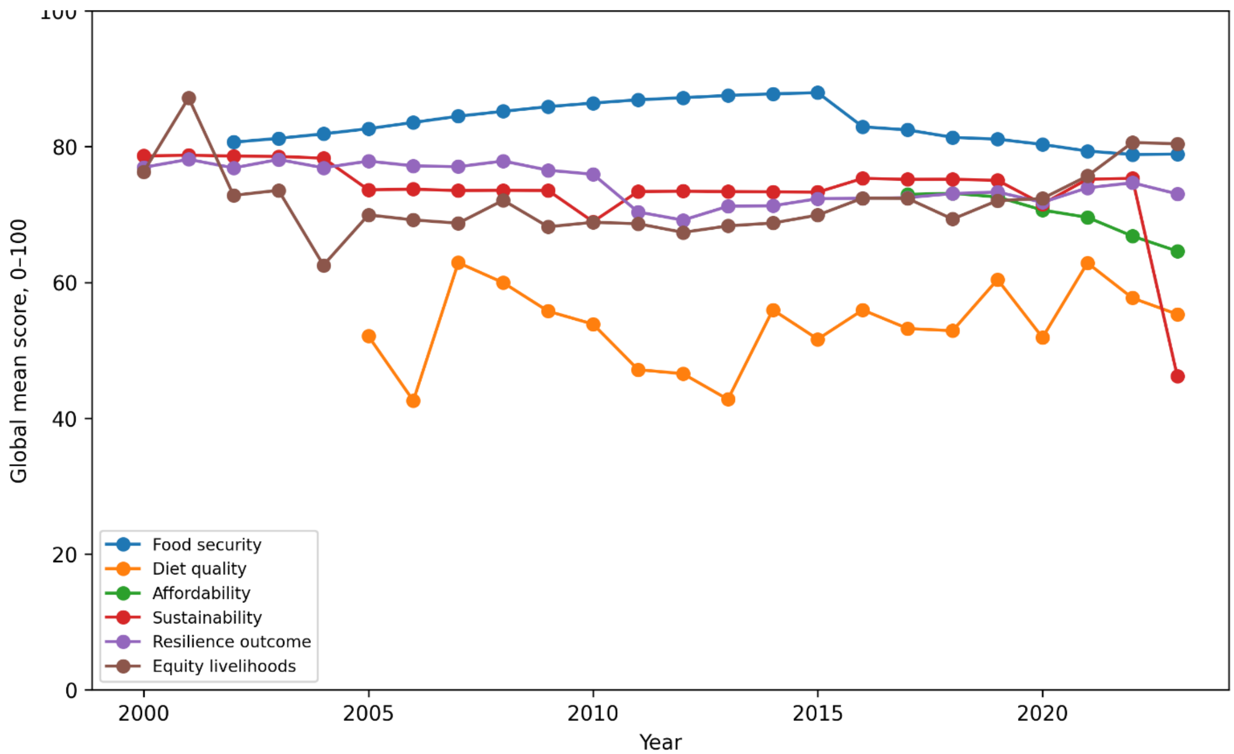


Source: Author's calculations using Food Systems Countdown Initiative (2025) data, 2000–2023.

Note: The figure reports global mean FSTPI trends under equal-weighted and interdependence-adjusted constructions. Transformation performance does not improve as steadily as cognitive capacity, suggesting that stronger cognitive functions may be necessary but not sufficient for food systems transformation. Structural constraints, shocks, and implementation challenges remain important.

The outcome-domain trends show additional heterogeneity. Food security, diet quality, affordability, sustainability, resilience, and equity/livelihoods do not move uniformly. Some domains remain relatively stable, while others fluctuate or decline (Figure 5.11). This pattern is consistent with the multidimensional nature of food systems transformation. Progress in one domain does not guarantee progress in another, and trade-offs among nutrition, affordability, sustainability, resilience, and livelihoods may complicate aggregate transformation trajectories. This finding speaks directly to the food systems literature, which emphasizes that transformation requires integrated governance across multiple objectives rather than isolated improvements in single indicators (Ruben et al. 2021; Béné and Abdulai 2024).

Figure 5.11 Global trends by food systems transformation domain, 2000–2023



Source: Author's calculations using Food Systems Countdown Initiative (2025) data, 2000–2023.

Note: The figure reports global trends for individual transformation domains, including food security, diet quality, affordability, sustainability, resilience, and equity/livelihoods. The divergent trends illustrate that food systems transformation is multidimensional and uneven. This reinforces the need for cognitive capacities that allow systems to detect trade-offs, coordinate across sectors, and adapt policy responses over time.

5.4 Baseline Association Between Cognitive Capacity and Transformation Performance

The preferred lagged fixed-effects model yields a positive but imprecise association between cognitive capacity and transformation performance. The equal-weighted FSCCI coefficient is 0.073 (standard error = 0.062; p = 0.239; 95 percent CI: −0.048 to 0.194; N = 4,457 country-year observations across 194 countries). The positive sign is consistent with expectation. The equal-weighted baseline therefore does not, by itself, establish a statistically distinguishable within-country association between prior cognitive capacity and subsequent transformation performance.

The baseline estimate should therefore be interpreted cautiously. Its direction is consistent with the theoretical expectation, but its statistical imprecision means that support for the hypothesis comes from the pattern across specifications rather than from the equal-weighted model alone. The result remains compatible with literature emphasizing rigorous monitoring, governance and institutional shifts, and political processes in food systems transformation (Fanzo et al. 2021; Ruben et al. 2021; Béné and Abdulai 2024).

The result is especially important because it shifts attention from policy presence to policy functionality. A country may have food system strategies, monitoring systems, and formal institutions, yet still struggle if information does not reach decision-makers, feedback is ignored, agencies work in silos, or implementation capacity is weak. The FSCCI appears to capture this broader functional capacity.

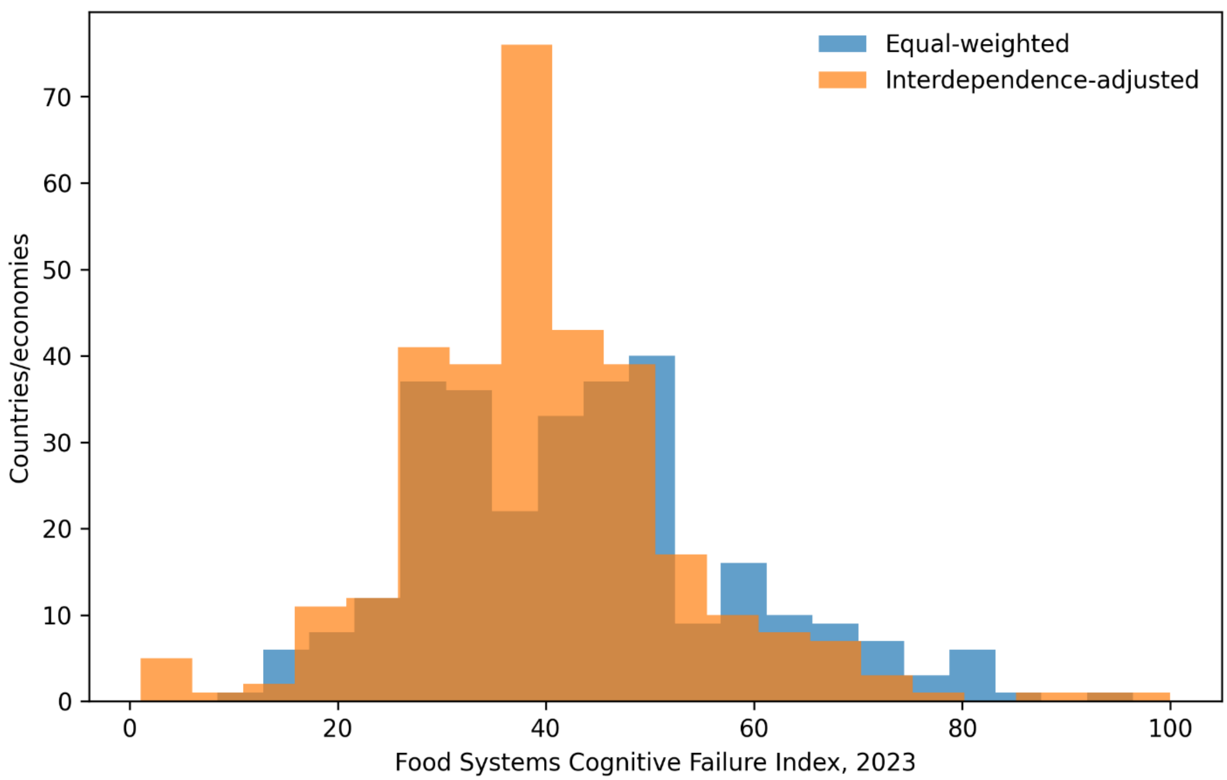
5.5 Cognitive Failure and Transformation Performance

The cognitive-failure specification provides the mirror image of the main result. Because the FSCFI is defined as the inverse of the FSCCI, the expected relationship with transformation performance is negative. The interpretation is straightforward: higher cognitive failure should be associated with weaker food systems transformation performance.

The cognitive failure framing is useful because it emphasizes the risks of fragmented sensing, weak transparency, poor coordination, limited feedback, and insufficient anticipatory capacity. Food systems can fail cognitively when they do not detect risks in time, evidence is not translated into policy, institutions do not coordinate across sectors, or systems are unable to prepare for shocks. This interpretation is consistent with food governance studies that identify policy silos, weak accountability, fragmented responsibilities, and coordination failures as barriers to transformation (Thow et al. 2022; Santo and Moragues-Faus 2018).

The distribution of cognitive failure scores in 2023 shows that failure is not concentrated at a single point but spread across a wide range of country experiences (Figure 5.12). The equal-weighted and interdependence-adjusted distributions overlap substantially, although the interdependence-adjusted version changes the shape of the distribution. This reinforces the idea that cognitive failure is not merely the absence of one capacity. It is a systems-level condition that emerges when weaknesses in information, feedback, coordination, implementation, and anticipation interact.

Figure 5.12 Distribution of cognitive failure scores, 2023



Source: Author's calculations using Food Systems Countdown Initiative (2025) data.

Note: The figure compares the distribution of equal-weighted and interdependence-adjusted cognitive failure scores in 2023. The spread of the distribution shows substantial cross-country variation in cognitive failure. The comparison between specifications suggests that cognitive failure is shaped not only by low scores in individual domains but also by the interaction among weaknesses across domains.

5.6 Alternative Weighting Results

The alternative weighting results show positive and statistically significant lagged associations. The PCA-weighted FSCCI coefficient is 0.107 (standard error = 0.052; p = 0.042; 95 percent CI: 0.004 to 0.209; N = 3,919; 187 countries). The interdependence-adjusted coefficient is 0.196 (standard error = 0.072; p = 0.006; 95 percent CI: 0.055 to 0.338; N = 4,457; 194 countries). Because the indexes have different distributions and scaling properties, coefficient magnitudes should not be compared as if they measured the same one-unit change. Table 5.1 summarizes these harmonized lagged fixed-effects estimates.

Table 5.1. Harmonized lagged fixed-effects estimates across FSCCI specifications

FSCCI specification	β	SE	p	95% CI	N	Countries
Equal-weighted	0.073	0.062	0.239	[-0.048, 0.194]	4,457	194
PCA-weighted	0.107	0.052	0.042	[0.004, 0.209]	3,919	187
Interdependence-adjusted	0.196	0.072	0.006	[0.055, 0.338]	4,457	194

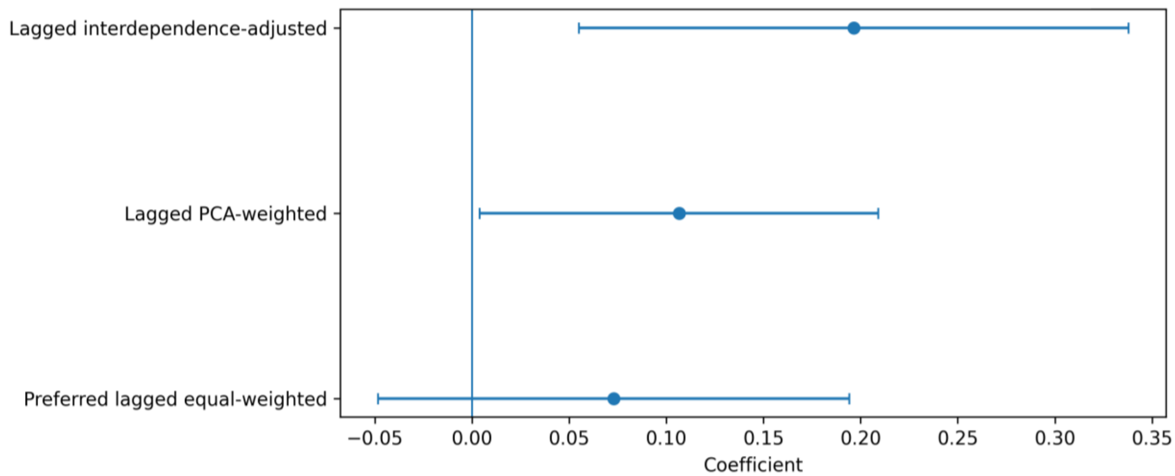
Source: Author's fixed-effects estimates using Food Systems Countdown Initiative (2025) data.

Note: All models regress FSTPI in year t on the indicated FSCCI in year t−1 and include country and year fixed effects. Standard errors are clustered by country. Samples differ because PCA requires complete observations across all six cognitive domains.

Persistence of the positive sign across specifications indicates that the direction of the result is not an artifact of equal weighting. However, the equal-weighted estimate is imprecise, so the evidence is better described as specification-sensitive rather than uniformly robust. The interdependence-adjusted coefficient is consistent with the theoretical importance of interacting domains, but it does not prove that interdependence causes better performance. That claim would require explicit modeling of interactions, thresholds, and alternative network structures.

This finding is consistent with resilience and governance research emphasizing interaction, feedback, learning, and cross-scale coordination as foundations of transformation (Wood et al. 2023; Hölscher et al. 2019). It also supports the broader claim that cognitive failure is a systems property: weaknesses in one domain can propagate through others and reduce the capacity of the whole food system to transform. Figure 5.13 visualizes the coefficients and 95 percent confidence intervals across the three FSCCI specifications.

Figure 5.13 Estimated association between lagged FSCCI specifications and food systems transformation performance



Source: Author's estimates from the models reported in Table 5.1.

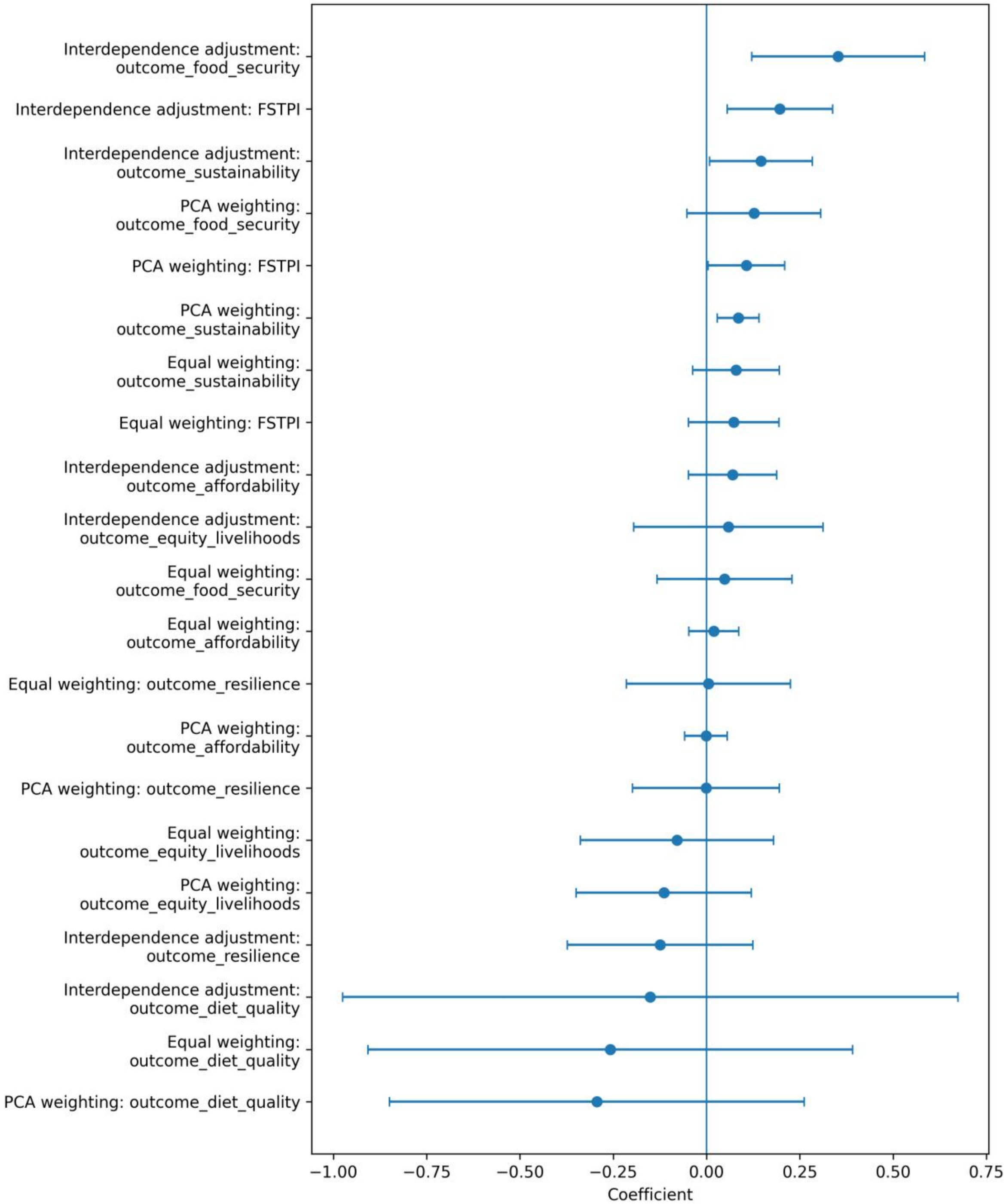
Note: The figure reports coefficients and 95 percent confidence intervals from the equal-weighted, PCA-weighted, and interdependence-adjusted models. All estimates are positive, but the equal-weighted confidence interval includes zero. The PCA and interdependence-adjusted estimates exclude zero. Differences in coefficient magnitude partly reflect different index scales and samples and should not be interpreted as direct evidence of amplification.

5.7 Outcome-Specific Associations

The outcome-specific coefficient plot shows that cognitive capacity is not associated with all transformation domains in the same way. Positive associations are strongest for some domains, particularly resilience and aggregate transformation performance, while estimates for other domains are weaker or less precise. This pattern is expected. Food systems transformation is multidimensional, and cognitive capacity may operate through some outcome channels more directly than others.

The stronger association with resilience is especially plausible. Resilience depends on the ability to detect risks, interpret signals, coordinate responses, and adapt under uncertainty. These are core cognitive functions. Similarly, sustainability and food security may benefit from stronger information systems and coordinated governance, although their outcomes are also shaped by structural and ecological factors. By contrast, diet quality and affordability may depend more directly on income, prices, market access, social protection, and household-level constraints, which may weaken the observed association with cognitive capacity in aggregate panel models (Figure 5.14).

Figure 5.14 Cognitive capacity predicts transformation outcomes across index versions



Source: Author's estimates using Food Systems Countdown Initiative (2025) data.

Note: The figure compares estimated associations between lagged cognitive-capacity indexes and specific transformation outcomes. The results show that the positive relationship is not uniform across all domains. Associations are generally stronger for aggregate transformation and resilience-related outcomes, while some domains show weaker or less precise estimates. This supports the interpretation of cognitive capacity as a broad enabling condition rather than a direct determinant of every transformation outcome.

The results provide four main findings. First, the FSCCI is empirically stable across alternative construction methods. The equal-weighted, PCA-weighted, and interdependence-adjusted indexes are highly correlated, indicating that the index captures a consistent underlying construct.

Second, food systems cognitive capacity varies substantially across countries and regions. High-capacity systems tend to display stronger information, feedback, coordination, administrative, and anticipatory functions, while high cognitive-failure systems show weaknesses across these same domains.

Third, the preferred equal-weighted lagged model is positive but statistically imprecise, while the PCA and interdependence-adjusted lagged models are positive and statistically significant. The evidence therefore supports a directionally consistent but specification-sensitive relationship rather than a uniformly significant baseline finding.

Fourth, the association remains positive under PCA-weighted and interdependence-adjusted specifications. The interdependence-adjusted model produces the largest coefficient, reinforcing the theoretical argument that cognitive domains interact and that cognitive capacity is a systems property.

Overall, the findings suggest that food systems cognitive capacity is a useful diagnostic lens for understanding why some food systems appear better able to transform than others. The evidence does not establish causality, but it shows that cognitive capacity is measurable, empirically stable, and meaningfully associated with transformation performance. Food systems that can sense problems, learn from feedback, coordinate actors, implement decisions, and anticipate shocks are better positioned to pursue healthier, more sustainable, more resilient, and more equitable outcomes. Conversely, food systems marked by cognitive failure may struggle to transform even when policies, institutions, or investments are formally present.

6. Robustness Checks

A central concern in composite-index research is whether empirical findings reflect a meaningful underlying relationship or are driven by specific modeling choices. For the FSCCI, this concern is particularly important because the index combines multiple domains, indicators, normalization decisions, weighting assumptions, and data availability rules. The positive association between cognitive capacity and food systems transformation performance reported in Section 5 could, in principle, arise from the way the index is constructed, the influence of one dominant domain, uneven patterns of missing data, regional composition effects, or the absence of relevant control variables.

This section evaluates those possibilities. The robustness checks examine whether the main finding remains visible when the FSCCI is reconstructed under alternative weighting assumptions, individual cognitive domains are removed, stricter missing-data rules are applied, additional control variables are introduced, region-specific heterogeneity is considered, and the association is estimated for individual transformation outcomes. The purpose is not to establish definitive causality. Rather, the purpose is to assess whether the empirical relationship between cognitive capacity and transformation performance is stable enough to support the paper's diagnostic claim.

Overall, the robustness results show that coefficient signs are broadly positive, but statistical precision and magnitude vary materially across specifications. The equal-weighted lagged estimate and several controlled models are imprecise, whereas the PCA and interdependence-adjusted models are more precisely estimated. This pattern supports a cautious interpretation: the construct is empirically stable, but its relationship with transformation outcomes is specification-sensitive and shaped by context, measurement choices, data availability, and broader structural conditions.

6.1 Robustness to Alternative Weighting Schemes

The first robustness exercise evaluates whether the main finding depends on the equal-weighted construction of the FSCCI. Equal weighting is useful because it is transparent and easy to interpret, but it also imposes the assumption that all six cognitive domains contribute equally to the overall index. To test whether the results are sensitive to this assumption, the analysis compares the baseline equal-weighted FSCCI with two alternative versions: a PCA-weighted index and an interdependence-adjusted index.

The results reported in Section 5 show that the PCA-weighted and interdependence-adjusted lagged indexes are positively and significantly associated with transformation performance. Their positive signs are consistent with the equal-weighted estimate, although the equal-weighted model is less precise. These results indicate that the direction of the association is not generated solely by the equal-weighting rule, but they do not remove sensitivity to index scale, sample, or construction.

This is important conceptually. If the relationship disappeared under PCA weighting or interdependence adjustment, the interpretation of cognitive capacity as a coherent systems property would be weaker. Instead, the persistence of the positive association across weighting strategies indicates that the FSCCI captures a stable empirical signal. The result also supports the theoretical claim that food systems transformation depends on interacting capacities rather than isolated institutional traits. Sensing, feedback, coordination, integrated problem framing and policy analysis, administrative and implementation capacity, and anticipatory and adaptive resilience are not independent functions. They reinforce one another through information flows, decision processes, and adaptive responses.

The stronger result for the interdependence-adjusted specification is especially meaningful. It suggests that food systems may perform better when cognitive functions are mutually reinforcing. A system that can sense emerging risks but cannot coordinate actors may still fail to respond. A system that monitors outcomes but lacks administrative and implementation capacity may fail to translate learning into implementation. A system that has formal policies but weak feedback mechanisms may be unable to adapt. This interpretation is consistent with governance and resilience scholarship emphasizing learning, coordination, cross-scale interaction, and adaptive capacity as central to transformation (Hölscher et al. 2019; Wood et al. 2023).

6.2 Leave-One-Domain-Out Robustness

The second robustness exercise tests whether the baseline association is driven by any single cognitive domain. This is important because a composite index may appear predictive simply because one component dominates the relationship. For example, if administrative and implementation capacity alone were responsible for the association with transformation performance, then the FSCCI would be less convincing as a multidimensional measure of cognitive capacity.

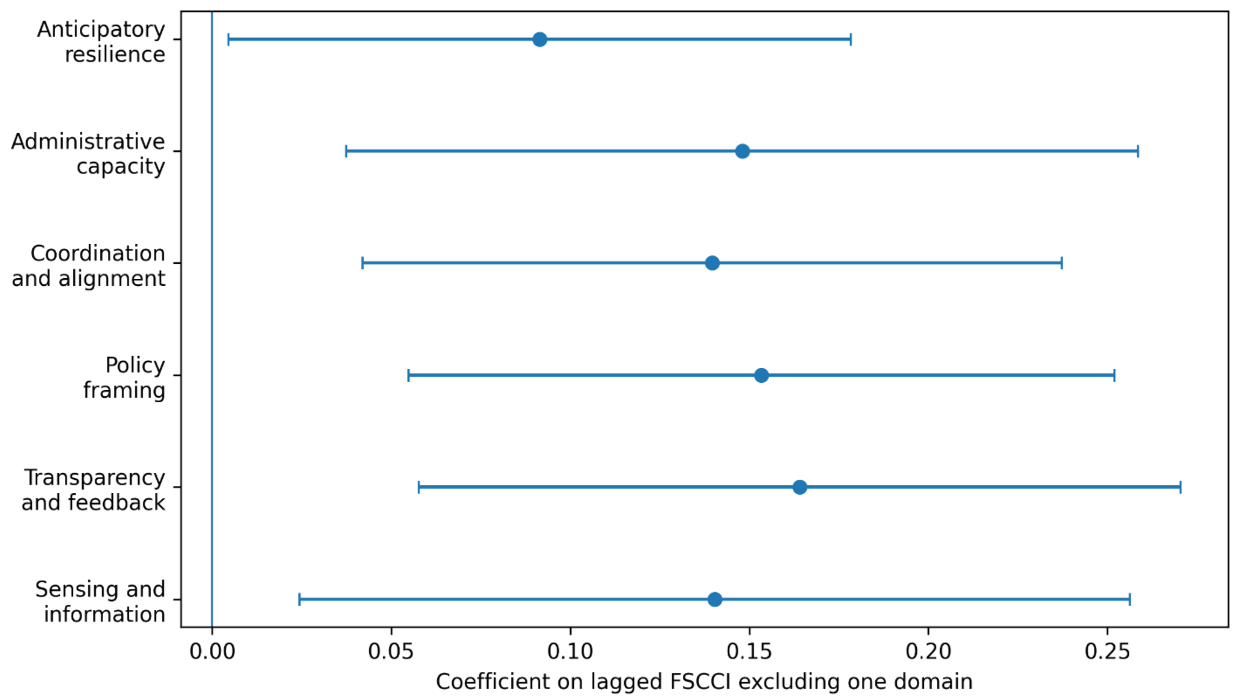
To examine this possibility, the index is recalculated several times, each time excluding one of the six cognitive domains: sensing and evidence, transparency, feedback, and learning, integrated problem framing and policy analysis, collective action and coordination, administrative and implementation capacity, and anticipatory and adaptive resilience. The transformation model is then re-estimated using each reduced version of the index.

The results show that the positive relationship between cognitive capacity and transformation performance persists across all six exclusions (Figure 6.1). Coefficient magnitudes vary, but the substantive conclusion remains unchanged. This indicates that the baseline association is not driven entirely by one domain. Instead, the FSCCI appears to capture a broader multidimensional pattern.

This finding is theoretically important. It supports the paper's central claim that food systems cognitive capacity is a systems property. Transformation depends not only on whether a food system can gather information or has formal policies, or whether public institutions can implement decisions. It depends on the interaction of these capacities. Removing one domain weakens or alters the profile of the index, but it does not eliminate the overall positive association.

The leave-one-domain-out results also speak directly to the governance literature. Food systems transformation requires coordination across sectors, learning from monitoring, institutional responsiveness, and the ability to manage complexity (Fanzo et al. 2021; Ruben et al. 2021; Béné and Abdulai 2024). The persistence of the result after removing individual domains is consistent with that broader view: transformation is enabled by a bundle of governance and information-processing capacities rather than a single institutional feature.

Figure 6.1 Leave-one-domain-out robustness for aggregate transformation



Source: Author's fixed-effects estimates using FSCI data.

Note: The figure reports estimated associations between transformation performance and versions of the FSCCI that exclude one cognitive domain at a time. The positive estimates across all exclusions indicate that the main result is not driven solely by sensing, feedback, integrated problem framing and policy analysis, coordination, administrative and implementation capacity, or anticipatory and adaptive resilience. This supports the interpretation of cognitive capacity as a multidimensional systems property.

6.3 Sensitivity to Missing-Data Rules

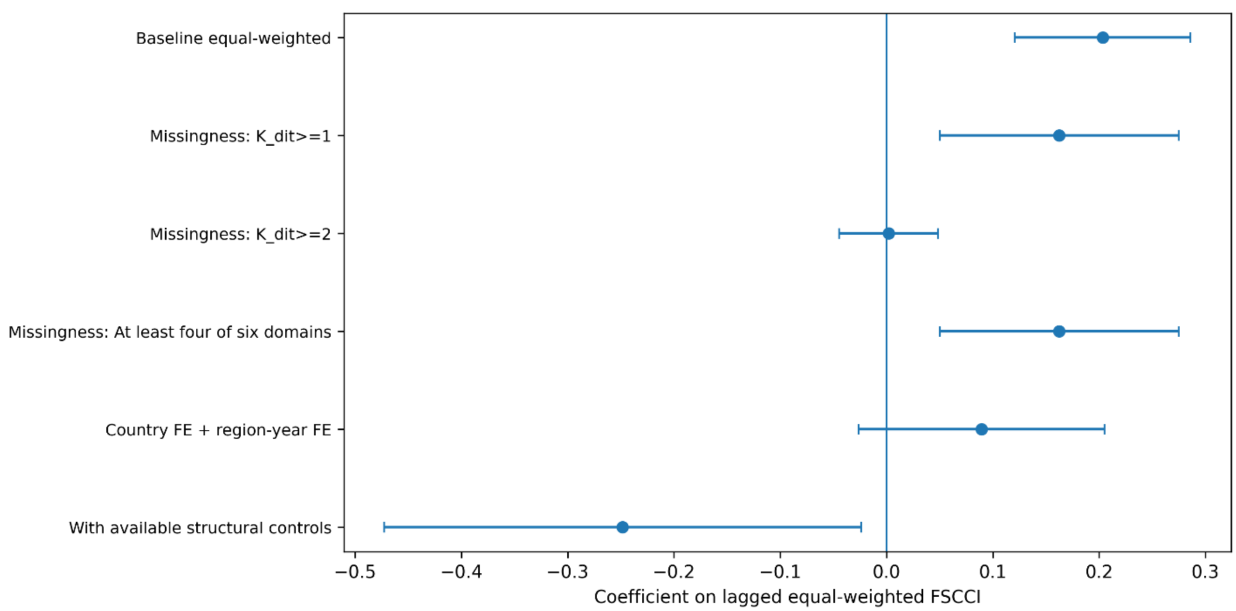
The third robustness exercise examines whether the findings are sensitive to missing data. This is a major concern in cross-country food systems research because indicator coverage varies by country, year, and domain. Countries with stronger statistical systems may have more complete data, while fragile states, small states, and lower-capacity systems may have more missing observations. If not handled carefully, these patterns can affect index construction and estimation results.

The baseline FSCCI uses available-indicator averaging. This approach maximizes country-year coverage and allows the analysis to use all available information. However, it may also produce domain scores based on relatively sparse data in some country years. To test whether this affects the findings, the analysis applies stricter missing-data thresholds. These include requiring more indicators within domains and requiring broader coverage across cognitive domains.

The results reported in Figure 6.2 show that the positive association between cognitive capacity and transformation performance remains visible under stricter data availability rules, although the magnitude and precision of the estimates vary. This pattern is reassuring but also cautionary. It suggests that the main result is not simply an artifact of the most permissive missing-data rule. At the same time, the variation across thresholds indicates that measurement coverage matters and should be reported transparently.

This finding is particularly relevant for the interpretation of cognitive capacity. Some food systems may appear cognitively weak because they lack governance capacity, while others may appear weak because data are incomplete. These two issues are related but not identical. Weak statistical systems may themselves be part of cognitive failure, because they limit the ability of institutions to sense problems and learn from feedback. However, missing data can also create measurement uncertainty. For that reason, the robustness checks should be interpreted as evidence that the baseline pattern is stable, while acknowledging that indicator coverage remains a limitation.

Figure 6.2 Core robustness checks for aggregate transformation performance



Source: Author's fixed-effects estimates using study data.

Note: The figure summarizes the estimated association between cognitive capacity and aggregate transformation performance under alternative robustness specifications, including stricter missing-data thresholds and additional model adjustments. The results show that the positive association generally persists, but coefficient magnitudes and precision vary. This indicates that the finding is robust in direction while still sensitive to data coverage and specification choices.

6.4 Robustness to Additional Structural and Country-Year Controls

The fourth robustness exercise examines whether the preferred lagged association reflects broader structural and time-varying country conditions. Table 6.1 reports a transparent sequence of two-way fixed-effects models. The non-overlapping controls are log GDP per capita, conflict-related deaths per 100,000 people, agriculture's share of GDP, Notre Dame Global Adaptation Initiative (ND-GAIN) climate readiness, log population, and food imports as a percentage of merchandise imports. Food price volatility and disaster damages are not entered as ordinary controls because they contribute to the anticipatory-capacity domain of the FSCCI; unemployment and underemployment are not entered because they contribute to the FSTPI.

Across the maximal available samples, the coefficient on lagged equal-weighted FSCCI is 0.073 (SE = 0.062; p = 0.239) in the baseline model. It is 0.078 after adding log GDP per capita, 0.074 after adding conflict exposure, 0.054 after adding agriculture's share of GDP, 0.057 after adding climate readiness, and 0.047 in the extended model that also includes population and food-import dependence. None of these estimates is statistically distinguishable from zero at conventional levels. The extended model uses 3,670 country-year observations from 182 countries.

Because the sequential models use different estimation samples, Panel B of Table 6.2 repeats the comparison on the 3,670-observation complete-case sample. On that common sample, the FSCCI coefficient declines from 0.068 (SE = 0.059; p = 0.250) in the baseline model to 0.054 with the core controls and 0.047 with the extended controls. The point estimate therefore falls by about 30 percent, but the confidence intervals overlap substantially.

Table 6.1 Controlled two-way fixed-effects estimates for aggregate transformation performance

Model	Specification	β	SE	p	95% CI	N	Countries
M1	Baseline	0.073	0.062	0.239	[-0.048, 0.194]	4,457	194
M2	+ log GDP per capita	0.078	0.062	0.215	[-0.045, 0.200]	4,346	192
M3	+ conflict exposure	0.074	0.063	0.238	[-0.049, 0.197]	4,346	192
M4	+ agriculture share of GDP	0.054	0.064	0.402	[-0.072, 0.179]	4,288	191
M5	+ climate readiness	0.057	0.064	0.375	[-0.069, 0.182]	4,280	190
M6	+ population and food-import dependence	0.047	0.058	0.416	[-0.067, 0.161]	3,670	182
S1	Same-sample baseline	0.068	0.059	0.250	[-0.048, 0.183]	3,670	182
S2	Same-sample core controls	0.054	0.059	0.356	[-0.061, 0.170]	3,670	182
S3	Same-sample extended controls	0.047	0.058	0.416	[-0.067, 0.161]	3,670	182

Source: Author's estimates using FSCI data and the external control variables described in Section 6.4.

Note: The dependent variable is FSTPI. β is the coefficient on one-year-lagged equal-weighted FSCCI. All models include country and year fixed effects, with standard errors clustered by country. M1–M6 use the maximal available sample for each specification. S1–S3 use the common complete-case sample for M6. Core controls are log GDP per capita, conflict exposure, and agriculture's share of GDP.

The controlled results support a cautious interpretation. The estimated association remains positive, but it is imprecise in every equal-weighted controlled specification. The results do not establish an independent causal effect of cognitive capacity, and individual control coefficients should not be interpreted causally because some structural measures may be endogenous, highly skewed, or measured with error. The main inference is that the sign is stable while the magnitude is modestly sensitive to controls and sample composition.

6.5 Regional, Scale, Climate-Readiness, and Import-Dependence Heterogeneity

The fifth robustness exercise examines whether the association varies across regions and with national scale, climate readiness, and reliance on imported food. These checks respond to the possibility that coordination costs differ by country size, that climate-prepared countries receive stronger anticipatory capacity scores, and that import-dependent economies are evaluated differently from systems that rely more heavily on domestic production.

Table 6.3 reports region-specific estimates. Latin America and the Caribbean is the only region with a positive coefficient that remains statistically significant in both the unadjusted model ($\beta = 0.220$; SE = 0.076; $p = 0.004$) and the core-controlled model ($\beta = 0.198$; SE = 0.087; $p = 0.023$). Central Asia has a negative coefficient in both models, but the estimate is based on only five countries and conventional cluster-robust inference is unreliable with so few clusters. The remaining regional estimates are imprecise. A pooled region-interaction model rejects equality of the regional slopes ($\chi^2(8) = 24.65$; $p = 0.0018$), confirming heterogeneity but not identifying a single general regional pattern.

Table 6.2 Operationalization and 2023 coverage of regional, scale, climate-readiness, and import-dependence heterogeneity

Dimension	Operationalization and model	2023 coverage and reference distribution	Interpretive purpose and caution
Region	FSCI regional classification; estimate separate regional two-way fixed-effects models and a pooled FSCCI × region interaction model.	2023 classification coverage: N = 218 across 9 regions. The baseline regression sample contains 194 countries: Sub-Saharan Africa 48; North America and Europe 45; Latin America and Caribbean 34; North Africa and West Asia 23; Oceania 14; Southeast Asia 11; South Asia 9; Central Asia 5; East Asia 5.	Tests whether the FSCCI–FSTPI association is context dependent. Very small regional cells, especially North America and South Asia, should not be treated as precise standalone estimates.
Population scale	Log population, standardized over the panel; interact contemporaneous population scale with lagged FSCCI.	2023 coverage: N = 208. Q1 = 1.32 million; median = 7.34 million; Q3 = 28.32 million.	Tests whether coordination costs rise with population. No monotonic small-state advantage is assumed because small states may also have thin administrative, statistical, and implementation capacity.
Geographic scale	Log land area, standardized over the panel; interact geographic scale with lagged FSCCI.	2023 coverage: N = 208. Q1 = 13,135 km^2; median = 99,215 km^2; Q3 = 470,625 km^2.	Tests whether geographic reach, service delivery, and coordination across dispersed territories condition the association. Land area is nearly time invariant, so its interaction—not its absorbed main effect—is informative in country fixed-effects models.
Climate readiness	ND-GAIN readiness score (0–1), standardized over the panel; interact contemporaneous readiness with lagged FSCCI.	2023 coverage: N = 192. Q1 = 0.305; median = 0.392; Q3 = 0.509.	Tests whether high anticipatory-resilience scores partly reflect broader climate readiness. Because readiness may overlap conceptually with FSCCI components, estimates are interpreted as sensitivity checks rather than independent causal effects.
Food-import dependence	Food imports as a percentage of merchandise imports, standardized over the panel; interact contemporaneous import dependence with lagged FSCCI.	2023 coverage: N = 159. Q1 = 9.9%; median = 13.6%; Q3 = 18.7%.	Tests whether trade structure helps explain unusual rankings among import-reliant economies. The measure captures the composition of merchandise imports; it is not a direct measure of caloric import dependence, food self-sufficiency, or exposure to foreign-exchange constraints.

Source: Author's calculations from Global Country Indicators, 1995–2025.

Note: Values are unweighted 2023 distributions; Q1 and Q3 denote the 25th and 75th percentiles. Because coverage differs by measure, interaction models should report the estimation sample and use a common complete-case sample when comparing coefficients across heterogeneity dimensions.

Table 6.3 Region-specific FSCCI–FSTPI estimates

Region	Specification	β	SE	p	95% CI	N	Countries
Central Asia	Unadjusted	-0.702	0.231	0.002	[-1.155, -0.249]	115	5
Central Asia	Core controls	-0.561	0.142	<0.001	[-0.839, -0.283]	114	5
East Asia	Unadjusted	-0.155	0.763	0.839	[-1.651, 1.340]	115	5
East Asia	Core controls	0.909	0.532	0.087	[-0.133, 1.951]	91	4
Latin America and Caribbean	Unadjusted	0.220	0.076	0.004	[0.071, 0.368]	781	34
Latin America and Caribbean	Core controls	0.198	0.087	0.023	[0.027, 0.368]	755	33
North Africa and West Asia	Unadjusted	0.092	0.174	0.599	[-0.250, 0.433]	529	23
North Africa and West Asia	Core controls	-0.024	0.165	0.886	[-0.348, 0.300]	512	23
North America and Europe	Unadjusted	0.118	0.164	0.474	[-0.204, 0.439]	1,032	45
North America and Europe	Core controls	0.087	0.189	0.645	[-0.283, 0.457]	989	44
Oceania	Unadjusted	-0.003	0.114	0.981	[-0.226, 0.221]	321	14
Oceania	Core controls	0.003	0.109	0.981	[-0.211, 0.217]	319	14
Southeast Asia	Unadjusted	-0.236	0.216	0.274	[-0.660, 0.187]	253	11
Southeast Asia	Core controls	-0.220	0.278	0.429	[-0.765, 0.325]	251	11
South Asia	Unadjusted	-0.329	0.497	0.509	[-1.304, 0.646]	207	9
South Asia	Core controls	-0.406	0.436	0.352	[-1.262, 0.449]	204	9
Sub-Saharan Africa	Unadjusted	-0.072	0.123	0.560	[-0.314, 0.170]	1,104	48
Sub-Saharan Africa	Core controls	0.004	0.121	0.974	[-0.234, 0.242]	1,053	48

Source: Author’s estimates using FSCI data and the external control variables described in Section 6.4.

Note: Separate regional models include country and year fixed effects and country-clustered standard errors. Core controls are log GDP per capita, conflict exposure, and agriculture’s share of GDP. Estimates based on fewer than 20 countries should be treated as descriptive because conventional cluster-robust inference may be unreliable.

Table 6.4 Continuous heterogeneity interactions

Moderator	Specification	Interaction β	SE	p	95% CI	N	Countries
Population scale	Moderator-specific maximal sample	-0.010	0.038	0.799	[-0.084, 0.065]	4,435	193
Population scale	Common complete-case sample	0.041	0.038	0.277	[-0.033, 0.116]	3,685	182
Population scale	Common sample + core controls	0.025	0.036	0.497	[-0.046, 0.096]	3,662	182
Land-area scale	Moderator-specific maximal sample	-0.078	0.031	0.012	[-0.140, -0.017]	4,403	193
Land-area scale	Common complete-case sample	-0.045	0.044	0.315	[-0.131, 0.042]	3,685	182
Land-area scale	Common sample + core controls	-0.058	0.042	0.169	[-0.142, 0.025]	3,662	182
Climate readiness	Moderator-specific maximal sample	0.080	0.033	0.015	[0.016, 0.143]	4,412	192
Climate readiness	Common complete-case sample	0.108	0.037	0.003	[0.036, 0.180]	3,685	182
Climate readiness	Common sample + core controls	0.118	0.037	0.002	[0.045, 0.191]	3,662	182
Food-import dependence	Moderator-specific maximal sample	-0.124	0.036	<0.001	[-0.195, -0.053]	3,700	182
Food-import dependence	Common complete-case sample	-0.116	0.036	0.001	[-0.187, -0.044]	3,685	182
Food-import dependence	Common sample + core controls	-0.107	0.037	0.004	[-0.179, -0.035]	3,662	182

Source: Author’s estimates using FSCI data and variables described in Section 6.5.

Note: Each moderator is standardized over the country-year panel. The interaction coefficient is the change in the FSCCI slope associated with a one-standard-deviation increase in the moderator. Common-sample models require non-missing values for all four moderators; adjusted models also include the three core controls. All models include country and year fixed effects and country-clustered standard errors.

The continuous interaction results in Table 6.4 sharpen the scale and structural interpretation. In the adjusted common sample of 3,662 observations from 182 countries, population scale does not moderate the association (interaction $\beta = 0.025$; SE = 0.036; $p = 0.497$). The land area interaction is negative in the maximal sample, but it is smaller and not statistically significant in the adjusted common sample ($\beta = -0.058$; SE = 0.042; $p = 0.169$). Climate readiness positively moderates the association ($\beta = 0.118$; SE = 0.037; $p = 0.0016$), whereas food-import dependence negatively moderates it ($\beta = -0.107$; SE = 0.037; $p = 0.0035$).

The implied marginal slopes are consistent with these interactions. At one standard deviation above the mean of climate readiness, the FSCCI slope is 0.143 (SE = 0.066; $p = 0.032$); at one standard deviation below the mean, it is −0.093 and not statistically significant. At one standard deviation below the mean of food-import dependence, the slope is 0.153 (SE = 0.069; $p = 0.027$), whereas at one standard deviation above the mean, it is −0.062 and not statistically significant. These exploratory interactions should not be interpreted causally; they indicate that the diagnostic meaning of FSCCI differs with climate preparedness and trade structure.

6.6 Outcome-Specific Robustness

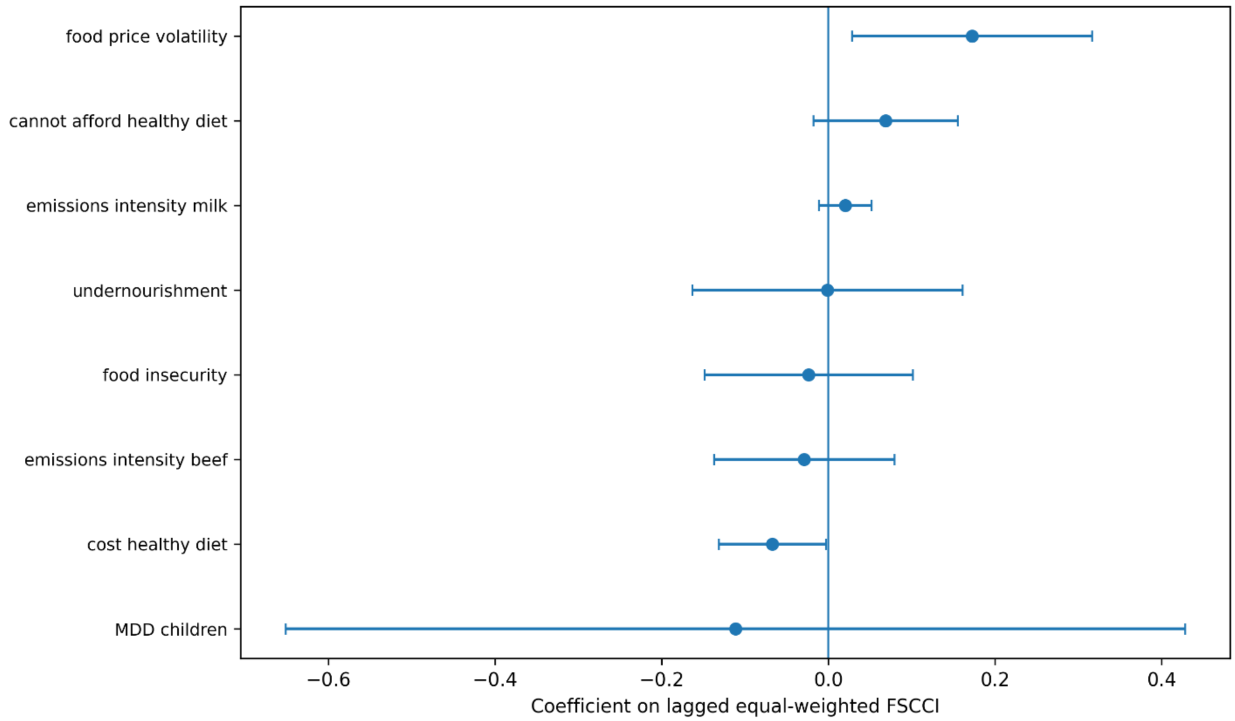
The sixth robustness exercise investigates whether cognitive capacity is associated with specific transformation outcomes or only with the aggregate FSTPI. This is important because food systems transformation is multidimensional. A country may improve resilience without improving diet quality or strengthen sustainability even as affordability remains under pressure. An aggregate index can obscure these domain-specific patterns.

The outcome-specific results show that cognitive capacity is not equally associated with all transformation domains (Figure 6.3). The association appears stronger and more precise for some outcomes than for others. In particular, resilience-related and aggregate transformation outcomes show clearer positive associations, while some diet, affordability, and nutrition-related measures are weaker or less precisely estimated.

This pattern is substantively plausible. Cognitive capacity should be especially relevant for outcomes that depend on sensing risks, coordinating responses, anticipating shocks, and adapting institutions. Resilience, for example, is closely linked to the ability to detect instability, process information, and respond under uncertainty. Sustainability may also benefit from stronger monitoring and policy coordination. By contrast, diet quality and affordability are shaped by many additional forces, including income, household purchasing power, market access, food prices, social protection, and cultural preferences. Cognitive capacity may still matter for these outcomes, but its association may be less direct in aggregate cross-country models.

The outcome-specific results reinforce the interpretation of cognitive capacity as an enabling condition rather than a simple universal predictor. Stronger cognitive capacity may improve the ability of food systems to govern transformation, but it does not eliminate structural constraints or guarantee uniform progress across all outcomes.

Figure 6.3 Individual-outcome robustness



Source: Author's fixed-effects estimates using FSCI data.

Note: The figure reports estimated associations between lagged equal-weighted FSCCI and selected transformation outcomes. The estimates vary across outcomes, indicating that cognitive capacity is more strongly associated with some transformation dimensions than others. This supports the interpretation that cognitive capacity is a broad enabling condition, with especially relevant links to outcomes requiring coordination, adaptation, and resilience.

6.7 Policy-Pathway and Shock-Interaction Robustness

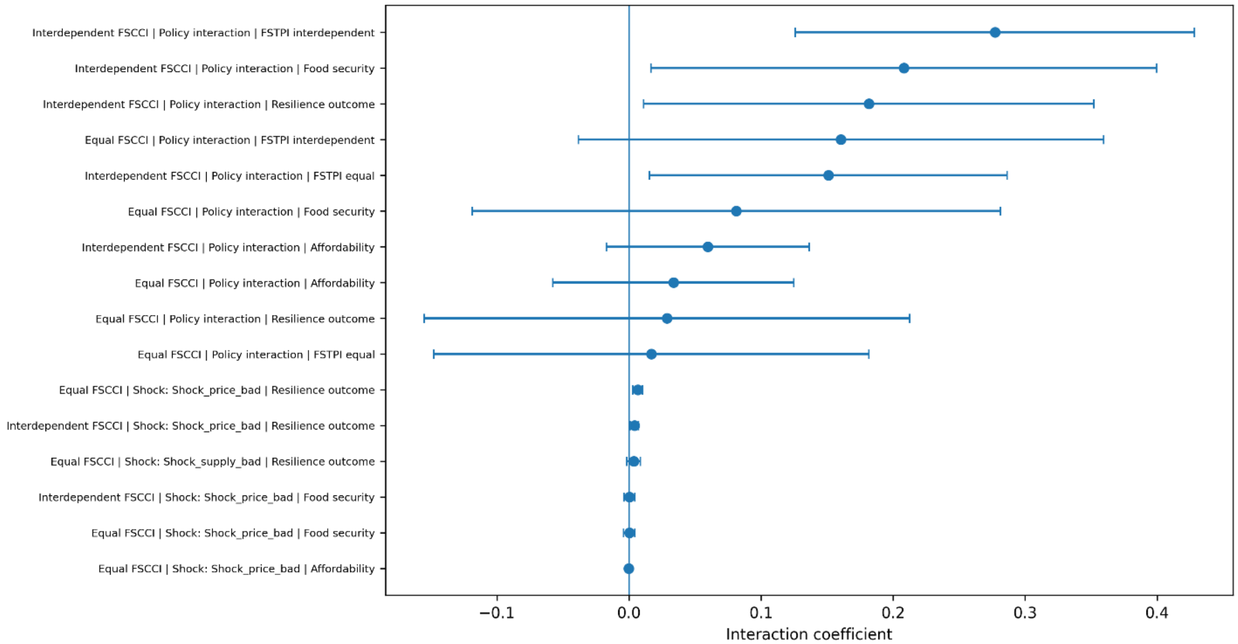
The robustness analysis also considers whether cognitive capacity conditions the relationship between policy presence, shocks, and transformation outcomes. These interaction models are exploratory and should not be interpreted as causal estimates. Their purpose is to assess whether food system policies and shocks are associated with outcomes differently depending on the level of cognitive capacity.

The policy-pathway results are motivated by a simple idea: formal policy commitments may matter more when food systems have the capacity to implement, monitor, coordinate, and learn from them. A national food systems pathway, right-to-food recognition, or food environment policy may have limited effect if the system lacks feedback mechanisms, administrative and implementation capacity, stakeholder coordination, or adaptive learning. Conversely, policy commitments may be more meaningful in systems that can convert formal plans into coordinated action.

The shock-interaction results are motivated by a related idea: cognitive capacity may buffer the negative effects of shocks. Food price volatility, supply variability, climate-related disasters, and economic disruptions may harm food system outcomes, but systems with stronger sensing, coordination, and anticipatory and adaptive resilience may be better able to absorb and respond to these disruptions. This interpretation aligns with resilience research emphasizing learning, diversity, feedback, and cross-scale coordination as foundations for managing food system instability (Wood et al. 2023).

The estimates from these interaction models should be interpreted cautiously because interaction effects in observational panel settings are sensitive to specification, measurement, and omitted variables. Nevertheless, the exercise is useful because it links the FSCCI to plausible mechanisms. Cognitive capacity may matter not only as a direct correlate of transformation performance, but also as a condition that shapes whether policies are effective and whether shocks become crises.

Figure 6.4 Policy and shock interaction estimates



Source: Author's exploratory interaction estimates using FSCI data.

Note: The figure presents exploratory interaction estimates showing whether cognitive capacity conditions the relationship between policy presence, shocks, and selected transformation outcomes. Positive interaction estimates are consistent with the idea that cognitive capacity may strengthen the effectiveness of policy commitments and help buffer adverse shocks. These results should be interpreted as exploratory rather than causal.

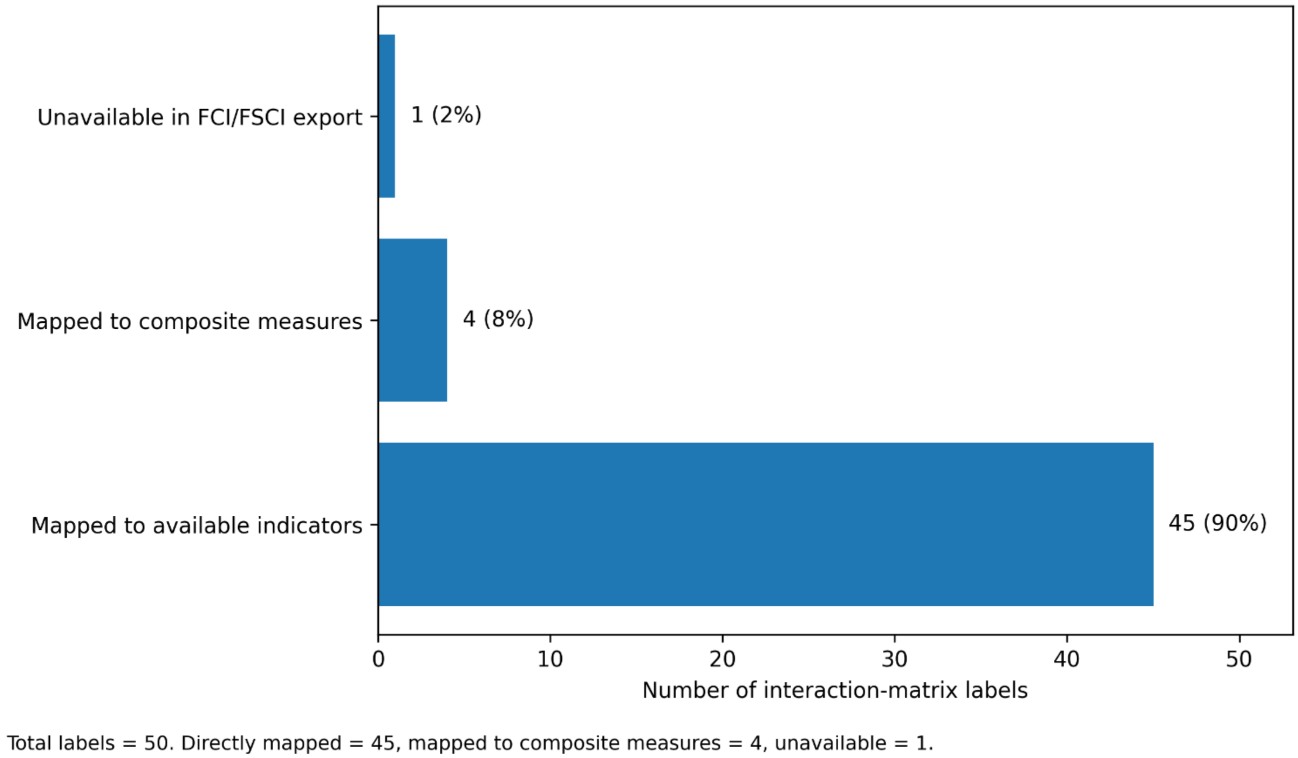
6.8 Coverage of the Interaction-Matrix Mapping

A final measurement check concerns the construction of the interdependence-adjusted index. Because this version of the FSCCI depends on mapping interaction-matrix (Schneider et al., 2025) labels to available food system indicators, it is important to examine the coverage of that mapping. If many conceptual labels cannot be matched to observed indicators, the interdependence adjustment may be incomplete or uneven.

Figure 6.5 shows that most labels were successfully mapped, while a smaller number were mapped to composite measures or were not available in the FCI/FSCI export. This supports the feasibility of the interdependence-adjusted approach but also highlights a measurement limitation. The adjusted index is only as strong as the indicator mapping on which it rests. Where conceptual domains are not fully represented in the available data, the interdependence structure may only partially capture the relationships theorized in the framework.

This is not a reason to discard the interdependence-adjusted index. Rather, it suggests that the index should be interpreted as a first empirical approximation of system interdependence. Future work could improve the mapping by expanding the indicator set, validating the interaction structure with expert input, or using network-based methods to model relationships among cognitive domains more explicitly.

Figure 6.5 Coverage of the interaction matrix to FCI/FSCI mapping



Source: Author's mapping of Schneider et al. (2025) interaction-matrix labels to available FCI/FSCI indicators.

Note: The figure summarizes how many interaction-matrix labels were successfully mapped to available indicators, mapped to composite measures, or unavailable in the FCI/FSCI export. The results show that the interdependence-adjusted index is empirically feasible, while also identifying areas where future data improvements could strengthen the measurement of cognitive-domain interactions.

The robustness checks clarify both the consistency and the limits of the findings. First, coefficient signs remain positive under alternative weighting schemes, but precision differs. Second, leave-one-domain-out models indicate that the result is not driven by a single component. Third, stricter missing-data rules preserve the broad direction while affecting magnitude and precision. Fourth, additional controls attenuate the estimates without generally reversing their signs. Fifth, regional and outcome-specific results show substantial heterogeneity. Finally, exploratory interaction results are consistent with possible policy and shock pathways but are not causal evidence.

These findings strengthen the paper's central claim: food systems cognitive capacity is a measurable and empirically meaningful feature of food systems transformation. The robustness evidence does not prove causality, but it shows that the core association is not easily explained away by weighting choices, individual domains, missing-data rules, or simple specification changes.

At the same time, the robustness checks also underscore the need for caution. Cognitive capacity is a latent construct measured through imperfect proxies. Data availability varies across countries and years. Some controls overlap conceptually with the index. Regional heterogeneity suggests that mechanisms differ across contexts. Outcome-specific variation shows that cognitive capacity is not equally related to every dimension of transformation. These limitations do not undermine the framework; rather, they define the appropriate interpretation. The FSCCI should be used as a diagnostic tool for understanding the information-processing, coordination, feedback, implementation, and anticipatory capacities of food systems.

Overall, the robustness results support the view that food systems transformation depends partly on the capacity of systems to sense, learn, coordinate, implement, and adapt. Food systems with stronger cognitive capacity appear better positioned to pursue transformation, while systems marked by cognitive failure may struggle to convert information, policies, and resources into improved outcomes.

7. Discussion

This study developed and tested food systems cognitive capacity as a diagnostic lens for transformation. The concept is intentionally broader than information processing: it is the collective governance capacity to convert diverse knowledge into coordinated, implemented, monitored, and adaptive action. The estimated lagged associations are positive across the equal-weighted, PCA, and interdependence-adjusted specifications, but the equal-weighted baseline is statistically imprecise. Heterogeneity across regions, outcomes, controlled models, and index constructions shows that cognitive capacity is a plausible enabling condition.

The contribution is integrative rather than terminological. Food systems research has long emphasized connected biophysical, economic, institutional, and social processes, while knowledge-systems, scholarship ono policy capacity, adaptive governance, and resilience identify different parts of the knowledge-to-action problem. The FSCCI brings these parts into a common six-domain framework, supplies a comparative measurement strategy, and identifies where system-level breakdowns may occur.

The results should therefore be read as evidence that the construct is measurable and potentially relevant for diagnostic purposes, not as proof that one unit of FSCCI causes a fixed improvement in transformation. High correlations among index versions indicate convergent stability. Positive fixed-effects coefficients indicate a common direction across specifications, although precision differs. Outcome-specific variation further indicates that the enabling role is not uniform across food system goals.

7.1 Food Systems as Knowledge-to-Action Systems

Food systems continuously generate scientific, administrative, market, ecological, and experiential knowledge. Cognitive capacity concerns whether this knowledge is retained, integrated, contested productively, and linked to authority, budgets, implementation routines, and learning. A system that collects data but cannot act on it remains weak; a system that acts without feedback may reproduce failure; and a system that has a formal strategy but lacks staff, coordination, and institutional memory may not sustain implementation.

This perspective connects monitoring to governance. Monitoring is not transformative simply because an indicator exists. It becomes governance infrastructure when responsibilities are assigned, data are interoperable and accessible, findings trigger review, affected groups can contest interpretation, and decision-makers have the authority and resources to respond (Cash et al. 2003; Fanzo et al. 2021).

The framework also clarifies the role of policy. A national pathway, right-to-food commitment, or food environment policy is a potentially important signal, but its effect depends on analytical, political, operational, and learning capacities. Formal adoption is therefore an input to a policy process, not a sufficient measure of transformation.

7.2 Understanding Cognitive Failure

Cognitive failure is not simply a lack of data. It includes failures of knowledge governance, problem framing, representation, coordination, execution, memory, and adaptation. Evidence may be available but politically inconvenient; ministries may have incompatible mandates; implementation units may lack recurrent budgets; or consultant-built systems may disappear when contracts end.

The last example is especially important for early warning and monitoring. A short-lived project can generate dashboards and reports without creating national capacity. Durable capacity requires a legally designated data custodian, government-owned repositories, interoperable standards, documented code and metadata, recurrent financing, local analyst and civil-service training, succession plans, and formal links between warnings and predefined decisions.

This distinction turns the FSCFI into a diagnostic rather than a stigma. A high score should prompt questions about where the chain breaks and whether the apparent weakness reflects institutions, political incentives, data coverage, or the fit of global indicators to a specific food system structure.

Country case studies are therefore indispensable. They can trace how information travels, who is authorized to interpret it, whose knowledge is excluded, how conflicts are resolved, and why a formal policy is—or is not—implemented.

7.3 Why Interdependence Matters

The theoretical value of interdependence is that it draws attention to bottlenecks and complementarity. Sensing without analysis may produce undigested data; analysis without political authorization may produce unused recommendations; coordination without implementation capacity may produce meetings; and implementation without feedback may lock in ineffective practice.

The larger coefficient for the interdependence-adjusted specification is consistent with this logic, but coefficient size alone cannot identify synergy. Future work should test alternative network structures, interactions, thresholds, and minimum-capacity conditions and should validate the assumed relationships through expert elicitation and case evidence.

The policy implication is sequencing. Capacity development may need to strengthen a binding bottleneck before investments elsewhere can produce returns. The relevant sequence will vary by context: one country may require basic sensing and statistical continuity, another may require coordination authority, and another may require implementation and budget systems.

This is also why the framework should not be reduced to a single ranking. Domain profiles, institutional histories, and political economy conditions are more useful for deciding where and how to intervene.

7.4 Interpreting the Outcome-Specific Results

The outcome-specific results show that cognitive capacity is not equally associated with all dimensions of transformation. The associations appear stronger for some outcomes, especially those related to aggregate transformation and resilience, while other domains show weaker or less precise relationships. This variation is important because it prevents overstatement of the findings.

Food systems transformation is multidimensional. Food security, diet quality, affordability, sustainability, resilience, and equity/livelihoods are connected, but they are not identical. Each domain is shaped by different mechanisms. Resilience depends strongly on the ability to anticipate shocks, process information, and coordinate responses. Sustainability may depend on monitoring, policy coherence, and long-term institutional learning. Food security may depend on production, access, markets, social protection, and crisis response. Diet quality and affordability are influenced by income, prices, consumer behavior, food environments, and distribution systems. The framework developed by the High Level Panel of Experts on Food Security and Nutrition (2017) is useful here because it shows that diets and nutrition emerge from the interaction of food supply chains, food environments, consumer behavior, and broader social, economic, and ecological drivers.

The FSCCI should therefore be understood as a broad enabling condition rather than a direct predictor of every outcome. Strong cognitive capacity may improve a food system's ability to recognize trade-offs, coordinate policy responses, and adapt over time, but it cannot by itself remove poverty, conflict, ecological constraints, or global market volatility. This is why the findings are strongest when interpreted diagnostically. Cognitive capacity helps explain why some systems may be better able to transform, but it does not eliminate the need to study material, political, economic, and environmental drivers of food system performance.

7.5 Policy Implications: From Diagnosis to Capacity Development

First, cognitive capacity and material investment are complements. Technology, infrastructure, finance, and formal policy can expand the feasible set of action, but their effects depend on the capacity to prioritize needs, coordinate actors, execute investments, maintain systems, monitor results, and revise course. Conversely, strong analysis and coordination without fiscal, human, and material resources may diagnose problems without resolving them.

Second, each FSCCI domain can be linked to a capacity development response. Weak sensing calls for interoperable statistical and surveillance systems, local data partnerships, and long-term trend monitoring. Weak feedback calls for evaluation routines, public reporting, review triggers, and institutional memory. Weak problem framing calls for multidisciplinary analytical teams and structured assessment of trade-offs. Weak coordination calls for authorized convening bodies, shared targets, aligned budgets, and procedures for resolving conflict. Weak implementation calls for staffing, procurement, enforcement, and recurrent financing. Weak anticipation calls for scenarios, contingency protocols, and exercises that connect warning to action.

Third, coordination capacity must be institutionalized rather than assumed. Comparative experience suggests that coordination is more durable when it has a legal or administrative mandate, a recognized convening authority, dedicated staff and financing, representation of affected groups, data-sharing procedures, and a routine for monitoring and revision. Regional food governance in the Pacific illustrates the importance of cross-scale arrangements, while trans-local food-policy networks show how learning can move across jurisdictions (Santo and Moragues-Faus 2019; Thow et al. 2022). Brazil's food security monitoring experience further illustrates how civil society participation and institutionalized monitoring can support governance (Kepple and Segall-Corrêa 2017).

Fourth, anticipatory capacity should be locally owned. Donor- or consultant-supported early warning systems should be designed around national custodianship: data and code retained in institutional repositories, open standards, local technical teams, recurrent budget lines, handover requirements, and partnerships with national universities. Preparedness also requires predefined decision protocols; an accurate warning that does not trigger authority, finance, or logistics is not an operational capacity.

Fifth, the FSCCI can support a capacity development strategy when combined with political economy analysis. The sequence proceeds as follows: diagnose the weakest and most consequential domain; map actors, interests, incentives, authority, and institutional constraints; identify technically appropriate and politically feasible reforms; assign organizational responsibility and financing; establish milestones; and monitor whether capacity becomes embedded rather than project dependent. The Kaleidoscope Model is useful at this stage because it examines agenda setting, design, adoption, implementation, and evaluation and reform, helping explain why a technically sound capacity reform may advance, stall, or be reversed (Resnick et al. 2015).

These implications favor using the index as a structured starting point for inquiry, not as an automatic prescription. Similar scores can arise from different domain combinations, and the feasible capacity building pathway depends on institutional history, political settlement, administrative structure, and available resources.

7.6 Implications for African Food Systems Transformation

The framework is particularly relevant to African food systems agendas because continental and national commitments require domestic systems that can generate evidence; coordinate across agriculture, nutrition, health, trade, environment, finance, and social protection; implement decisions and learn from results. Formal strategies and investment plans are necessary but insufficient when statistical systems are fragmented, platforms lack authority, implementation units depend on short-term projects, or feedback is not connected to budget and policy cycles.

A capacity development strategy should therefore be country specific. Where sensing is the bottleneck, priorities may include national data architecture, subnational reporting, and durable analytical teams. Where collective action is weak, priorities may include mandates, shared targets, ministerial coordination, and stakeholder representation. Where implementation is weak, the focus may be staffing, procurement, budget execution, and local administrative capability. Where anticipation is weak, early warning should be connected to contingency finance, logistics, and local ownership.

The political economy of these reforms matters. Capacity gaps can persist because fragmented mandates protect organizational turf, data confer power, coordination redistributes authority, or recurrent financing is less visible than capital projects. Tools such as the Kaleidoscope Model can help identify where reform coalitions, evidence, leadership, implementation incentives, and feedback mechanisms are likely to support or block change.

The FSCCI can support this process by establishing a baseline, identifying domain-specific bottlenecks, comparing peer countries with similar structures, and tracking whether capacity-building efforts persist. It should be complemented by national and subnational qualitative analysis, especially where global indicators poorly capture informal institutions, local knowledge, or implementation practice.

7.7 Limitations

Several limitations should be acknowledged. First, the analysis is associational rather than causal. The estimated relationship between cognitive capacity and transformation performance should not be interpreted as proof that cognitive capacity causes transformation. The models include country and year fixed effects, and the preferred specification uses lagged cognitive capacity, but time-varying omitted variables, reverse causality, and measurement error remain possible.

Second, cognitive capacity is a latent construct measured through observable proxies. Indicators such as public access to information, accountability, government effectiveness, social capital, food safety capacity, policy recognition, and resilience-related measures capture important aspects of system cognition, but they do not fully measure institutional learning, deliberation quality, political incentives, bureaucratic memory, or informal knowledge systems.

Third, the index depends on available cross-country data. Indicator coverage varies across countries and years. Some countries may appear cognitively weak partly because of limited reporting capacity. At the same time, limited reporting capacity may itself reflect a weakness in sensing and evidence systems. This creates an important interpretive challenge.

Fifth, several indicators overlap with broader governance and development measures. The revised definition acknowledges this overlap: cognitive capacity is proposed as a food system expression of knowledge-to-action and governance capacity, not as a wholly separate institutional substance. Discriminant validity should be tested against general governance, statistical capacity, policy capacity, and income measures.

Sixth, the interdependence-adjusted index depends on a specified interaction matrix. The current version approximates complementarity but does not demonstrate nonlinearity, causal interaction, or the correct direction of influence. Expert validation, alternative network structures, and case studies are needed.

Seventh, national averages can conceal subnational differences and may fit small states, federations, conflict-affected areas, and import-dependent economies differently. Country size, climate readiness, food-import dependence, and data coverage should accompany ranking interpretation.

Finally, the analysis is conducted at the national level. National averages may conceal subnational differences in governance capacity, food environments, ecological conditions, market access, conflict exposure, and vulnerability to shocks. Future work should explore whether cognitive capacity can be measured at subnational, city-region, or food system corridor levels.

7.8 Future Research

First, future work should test causal mechanisms around identifiable reforms that strengthen statistical systems, coordination mandates, transparency, implementation authority, or preparedness. Event studies, difference-in-differences, synthetic controls, or carefully matched case comparisons may be appropriate when assumptions are credible.

Second, construct validation should combine quantitative and qualitative evidence. Expert elicitation can assess domain content and weighting; confirmatory factor or latent-variable models can test measurement structure; and country process tracing can determine whether the indicators correspond to actual knowledge-to-action practices.

Third, mechanism-focused studies should test whether sensing improves resilience through earlier response, whether policy analysis reduces incoherence, whether coordination improves implementation, and whether feedback changes budget or regulatory decisions.

Fourth, subnational and city-region measures could reveal variation hidden by national averages and allow closer alignment between institutions, food environments, ecological zones, and implementation responsibilities.

Fifth, network approaches could examine which domains or organizations act as bottlenecks and whether minimum-capacity thresholds or nonlinear complementarities better explain transformation performance.

Finally, measurement should improve for leadership, informal institutions, local and Indigenous knowledge, bureaucratic memory, policy implementation quality, financing continuity, and the political incentives that shape whether evidence is used.

Finally, future research should improve measurement. Better indicators are needed for informal institutions, local knowledge systems, policy implementation quality, institutional learning, accountability practices, and adaptive governance. These dimensions are central to cognitive capacity but difficult to capture in current global datasets.

8. Conclusion

This paper introduces food systems cognitive capacity as the collective governance capacity to convert diverse knowledge into coordinated, implemented, monitored, and adaptive action. The construct does not replace material, financial, technological, human, political, or institutional explanations of transformation. It identifies the connective capacities through which those resources, policies, and investments are interpreted, combined, deployed, and revised.

The FSCCI and FSCFI organize this construct into six interdependent domains: sensing and evidence; transparency, feedback, and learning; integrated problem framing and policy analysis; collective action and coordination; administrative and implementation capacity; and anticipatory and adaptive resilience.

The empirical results show positive lagged coefficients across the equal-weighted, PCA-weighted, and interdependence-adjusted specifications. The equal-weighted coefficient is not statistically distinguishable from zero, while the PCA and interdependence-adjusted estimates are positive and statistically significant. Leave-one-domain-out and missing-data checks generally preserve the direction but not always the precision of the association.

These findings are diagnostic rather than causal. The index versions share indicators, data coverage is uneven, several measures overlap with broader governance, and results vary across regions and outcomes. Country rankings must therefore be interpreted with domain profiles, sample coverage, food-import dependence, national scale, climate readiness, and institutional context.

The cognitive failure perspective explains why formal policies, data, or investments may coexist with weak transformation. Knowledge may not circulate, problems may be framed too narrowly, organizations may lack authority to coordinate, implementation systems may be under-resourced, feedback may not trigger revision, or preparedness may remain disconnected from decisions.

The policy implication is not to choose capacity instead of investment. It is to design investments and reforms together with the sensing, analytical, coordination, implementation, learning, and anticipatory capacities required to make them functional and durable.

The FSCCI is therefore most useful as the first stage of a capacity development process: identify a bottleneck, investigate its institutional and political causes, select feasible reforms, assign ownership and recurrent financing, and track whether the capability becomes embedded in national and local organizations.

Future research should test causal mechanisms, validate the domain structure with experts and case studies, examine nonlinear interdependence, and develop subnational measures. More direct indicators are especially needed for leadership, institutional memory, local knowledge, implementation quality, and durable ownership of data and early warning systems.

The central conclusion is that food systems transformation depends not only on what systems have, but also on what their actors and institutions can collectively perceive, interpret, coordinate, implement, learn, and anticipate.

The framework is especially useful because it helps shift policy attention from formal commitment to functional capacity. A country may have a food systems strategy, a national pathway, or a policy commitment, but the transformative value of these instruments depends on whether the system can implement, monitor, learn, and adapt. Conversely, identifying cognitive failure can help policymakers locate the specific weaknesses that constrain transformation. In some settings, the binding constraint may be poor data and sensing capacity. In others, it may be weak feedback, fragmented coordination, limited administrative and implementation capacity, or insufficient shock preparedness.

Future research should extend this work in several directions. First, stronger causal designs are needed to test whether improvements in specific cognitive domains lead to subsequent gains in food systems outcomes. Second, mechanism-focused studies should examine how cognitive capacity operates through monitoring, policy coordination, implementation, resilience, and crisis response. Third, subnational analyses could reveal important variation hidden by national averages. Fourth, qualitative case studies could examine how information actually moves through institutions and how feedback is used in policy practice. Finally, future measurement work should improve indicators for informal institutions, local knowledge systems, policy implementation quality, institutional learning, and adaptive governance.

In conclusion, food systems cognitive capacity is a measurable construct with strong convergence across alternative index versions. Its estimated relationship with transformation performance is positive in direction but sensitive to specification: the equal-weighted lagged estimate is imprecise, whereas the PCA and interdependence-adjusted estimates are positive and statistically significant. Food systems that can sense problems, interpret feedback, coordinate actors, implement decisions, and anticipate shocks may be better positioned to pursue healthier, more sustainable, more resilient, and more equitable outcomes, but the present evidence remains diagnostic rather than causal.

The FSCCI and FSCFI therefore provide a structured way to diagnose not only whether food systems are transforming, but also whether they possess the cognitive capacity required to transform. This is the central insight of the paper: transformation depends not only on what food systems have, but on what food systems are able to perceive, learn, coordinate, and do.

Declaration of generative AI and AI-assisted technologies

During preparation of this manuscript, OpenAI's ChatGPT was used to support conceptual organization, code drafting, interpretation of preliminary outputs, and language editing. I reviewed all AI-assisted content, verified references and analytical claims, made all substantive methodological and interpretive decisions, and accepts full responsibility for the manuscript's accuracy, originality, and integrity.

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Annex

1. Purpose of the indexes

This technical note describes the construction of two related indexes used to diagnose cognitive performance in food systems: the FSCCI and the FSCFI. It also introduces an interdependence-adjusted version of the index that accounts for interactions among food system indicators.

The indexes are designed to measure whether a country's food system has the capacity to sense emerging problems, process information, coordinate actors, learn from feedback, interpret policy signals, anticipate shocks, and adapt decisions over time.

The empirical objective is to test whether stronger cognitive capacity is associated with better food systems transformation performance, and whether cognitive failure helps explain weak transformation outcomes despite the presence of policies, institutions, or investments.

2. Data structure

The analysis uses country-year data from the FSCI/Food Convergence Index database. The raw data are organized in long format as follows:

$\mathrm{Country}_i$, $\mathrm{ISO3}_i$, Region_i, $\mathrm{Indicator}_k$, StartYear, EndYear, Value_{kit}.

The dataset is reshaped into a country-year panel:

i=1,...,N,t=2000,...,2023,

where i indexes countries or economies, t indexes years, and k indexes indicators.

The transformed analytical dataset has the following structure:

$\mathrm{Country}_i$, $\mathrm{ISO3}_i$, Region_i, $Year_t$, $X_{1\mathrm{it}}$, $X_{2\mathrm{it}}$,...,X_{Kit},

where X_{kit} denotes the observed value of indicator kf or country or economy i in year t.

The main analytical period is 2000–2023 because most indicators on governance, policy, cognitive capacity, and transformation performance were available for this period.

3. Conceptual distinction between cognitive indicators and outcome indicators

A key methodological decision is to separate cognitive-capacity indicators from transformation-outcome indicators.

Cognitive-capacity indicators measure the ability of a food system to process information, interpret signals, coordinate actors, learn from feedback, and adapt over time. Transformation-outcome indicators measure realized food system performance.

This distinction is important because it reduces mechanical overlap between the explanatory variable and the dependent variable. In this framework, cognitive indicators are used to construct the FSCCI and the FSCFI, whereas outcome indicators are used to construct the FSTPI. Table A1 summarizes the conceptual separation between cognitive-capacity indicators and transformation-outcome indicators used in index construction.

Table A1. Distinction between cognitive-capacity and transformation-outcome indicators.

Indicator type	Purpose	Examples
Cognitive-capacity indicators	Measure sensing, feedback, coordination, interpretation, learning, implementation, and adaptive capacity.	Accountability, public access to information, open budget, civil society participation, social capital, government effectiveness, food safety capacity, integrated problem framing and policy analysis.
Transformation-outcome indicators	Measure realized food system performance.	Food security, diet quality, affordability, sustainability, resilience outcomes, equity, and livelihoods.

Source: Author's conceptualization.

Formally, let the full set of indicators be denoted by

$$\mathcal{K}.$$

This set is partitioned into two non-overlapping subsets:

$$\mathcal{K} = \mathcal{K}^C \cup \mathcal{K}^O, \mathcal{K}^C \cap \mathcal{K}^O = \varnothing,$$

where K^C denotes the set of cognitive-capacity indicators and K^O denotes the set of transformation-outcome indicators.

The cognitive-capacity index is constructed only from indicators in K^C, while the transformation-performance index is constructed only from indicators in K^O. This ensures that the empirical models do not use the same indicators on both sides of the regression equation.

4. Construction of the Food Systems Cognitive Capacity Index

4.1 Indicator selection and domains

The FSCCI is constructed from six cognitive domains. Each domain represents a distinct cognitive function that is theoretically relevant to food systems transformation.

Let the set of cognitive domains be denoted by

$$\mathcal{D}^C = \{\text{sensing,feedback,framing,coordination,administration,anticipation}\}.$$

Each domain $d \in D^C$ contains a set of indicators K_d^C, where K_d^C is the set of cognitive-capacity indicators assigned to domain d.

Table A2 maps the six FSCCI domains to their cognitive functions and illustrative indicators.

Table A2. Cognitive-capacity domains, functions, and illustrative indicators.

Domain	Cognitive function	Illustrative indicators
Sensing and evidence capacity	Detecting conditions, generating evidence, and transmitting signals.	Public access to information; mobile cellular subscriptions; food safety capacity.
Transparency, feedback, and learning	Enabling scrutiny, correction, accountability, and institutional learning.	Open Budget Index; V-Dem accountability; civil society participation; public access to information.
Integrated problem framing and policy analysis	Defining food system problems, trade-offs, and formal commitments in integrated terms.	National food systems pathway; food environment policies; legal recognition of the right to food.
Collective action and coordination	Aligning actors, authority, incentives, and knowledge across sectors and levels.	Civil society participation; social capital; Milan Urban Food Policy Pact population share.
Administrative and implementation capacity	Financing, staffing, executing, enforcing, and sustaining decisions.	Government effectiveness; food safety capacity.
Anticipatory and adaptive resilience	Using evidence to prepare for shocks and adapt under uncertainty.	Dietary sourcing flexibility; food supply variability; food price volatility; disaster damages relative to GDP.

Source: Author's mapping based on FSCI indicators.

The domain structure is intended to reflect the idea that food systems do not transform only through resource availability or policy presence. They also require the ability to perceive problems, interpret information, coordinate responses, implement decisions, and adapt under uncertainty.

4.2 Domain scores

Each cognitive domain score is calculated as the average of the available normalized indicators within that domain.

Let X_{kit}^* denote the normalized value of indicator k for country i in year t, scaled from 0 to 100 and oriented so that higher values indicate stronger cognitive capacity.

For each domain d, define the set of observed indicators as

$$\mathcal{K}_{dit}^{C} = \{k \in \mathcal{K}_{d}^{C} : X_{kit}^{*} \text{ is observed}\}.$$

Let

$$K_{dit}^{C} = | \mathcal{K}_{dit}^{C} |$$

denote the number of non-missing indicators available for domain d, country i, and year t.

The domain score is then calculated as

$$D_{dit}^{C} = \frac{1}{K_{dit}^{C}} \sum_{k \in \mathcal{K}_{dit}^{C}} X_{kit}^{*}, K_{dit}^{C} \geq 1.$$

where D_{dit}^{C} is the cognitive domain score for domain d, country i, and year t.

Thus, each domain score is an available-indicator average. This allows the index to use all available information while retaining a transparent and reproducible construction rule.

5. Indicator normalization

All indicators are transformed to a common 0–100 scale before domain scores are calculated. Normalization ensures that indicators measured in different units can be combined within the same index.

Let X_{kit} denote the raw value of indicator k for country i in year t. Let $\min(X_k)$ and $\max(X_k)$ denote the minimum and maximum observed values of indicator k across the analytical sample.

For indicators where higher raw values indicate stronger cognitive capacity or better transformation performance, the normalized indicator is calculated as

$$X_{kit}^{*} = 100 \times \frac{X_{kit} - \min(X_k)}{\max(X_k) - \min(X_k)}.$$

For indicators where higher raw values indicate weaker cognitive capacity or worse transformation performance, the normalized indicator is reverse-coded as

$$X_{kit}^{*} = 100 \times \frac{\max(X_k) - X_{kit}}{\max(X_k) - \min(X_k)}.$$

After normalization,

$$0 \le X_{kit}^{*} \le 100.$$

Higher normalized values always indicate a more desirable condition. For cognitive-capacity indicators, higher values indicate stronger cognitive capacity. For transformation-outcome indicators, higher values indicate stronger transformation performance.

This directional consistency is essential because the indexes are constructed as averages of normalized indicators. Without consistent directionality, high scores could combine positive and negative meanings, making the resulting index difficult to interpret.

When an indicator has no observed variation in the analytical sample, such that

$$\max(X_k) = \min(X_k),$$

the indicator cannot be min–max normalized. In that case, the indicator should either be excluded from index construction or assigned a neutral value only if there is a clear substantive justification. In the baseline implementation, such indicators should be excluded to avoid introducing artificial variation.

6. Treatment of categorical indicators

Categorical policy indicators are recoded into ordinal scores between 0 and 100 so that they can be combined with continuous indicators in the index.

The general coding principle is that higher values should represent stronger cognitive capacity, stronger policy recognition, or more comprehensive institutional coverage. Table A3 summarizes the coding rules applied to categorical policy indicators.

Table A3. Coding rules for categorical policy indicators.

Indicator type	Coding rule
Binary policy indicators	Yes; No.
Legal recognition of the right to food	Explicit constitutional or legal protection; implicit recognition; no recognition.
Food environment policy coverage	Both economic and regulatory measures; regulatory measures only; economic measures only; no relevant policy.

Source: Author's coding framework based on FSCI variables.

Formally, for a categorical indicator C_{kit}, the normalized score is assigned using a recoding function

$$X^*_{kit} = g_k(C_{kit}),$$

where $g_k(\cdot)$ maps each category of indicator k into a value on the 0–100 scale.

For example, for a binary policy indicator,

$$g_k(C_{kit}) = \begin{cases} 100, & \text{if the policy is present,} \\ 0, & \text{if the policy is absent.} \end{cases}$$

For the legal recognition of the right to food,

$$g_k(C_{kit}) = \begin{cases} 100, & \text{if recognition is explicit,} \\ 50, & \text{if recognition is implicit,} \\ 0, & \text{if recognition is absent.} \end{cases}$$

These coding decisions should be reported transparently because alternative codings may affect the policy-framing domain. In robustness checks, ordinal policy indicators can be recoded using alternative thresholds to assess whether results are sensitive to the assumed distance between categories.

7. Equal-weighted Food Systems Cognitive Capacity Index

The baseline FSCCI is calculated as the equal-weighted average of the six cognitive-domain scores.

Let $\mathcal{D}^C$ denote the set of cognitive domains, with

$$|\mathcal{D}^C| = 6.$$

The equal-weighted index is defined as

$$FSCCI^{EQ}_{it} = \frac{1}{6} \sum_{d \in \mathcal{D}^C} D^C_{dit}.$$

Equivalently, the index can be written as a weighted average:

$$FSCCI^{EQ}_{it} = \sum_{d \in \mathcal{D}^C} w_d \, D^C_{dit},$$

where

$$w_d = \frac{1}{|\mathcal{D}^C|} = \frac{1}{6}.$$

Thus,

$$\sum_{d \in \mathcal{D}^C} w_d = 1.$$

Equal weighting is used as the baseline because it is transparent, reproducible, and easy to interpret. It also avoids imposing statistically derived weights that may be sensitive to missing data, sample composition, or the correlation structure of the indicators.

Under this construction, each cognitive domain contributes equally to the overall index. A country-year receives a high FSCCI score only when it performs relatively well across the major cognitive functions of the food system, rather than only in one isolated area.

The index is bounded by

$$0 \leq FSCCI_{it}^{EQ} \leq 100.$$

Higher values indicate stronger food system cognitive capacity.

8. Missing data treatment

The baseline approach uses available-indicator averaging. This means that a domain score is calculated from the indicators that are observed for a given country-year.

For each cognitive domain d, the domain score is

$$D_{dit}^{C} = \frac{1}{K_{dit}^{C}} \sum_{k \in \mathcal{K}_{dit}^{C}} X_{kit}^{*}, K_{dit}^{C} \geq 1.$$

where $\mathcal{K}_{dit}{}^{C}$ is the set of observed cognitive-capacity indicators in domain d, and $K_{dit}{}^{C}$ is the number of available indicators in that domain for country i and year t.

The same rule is used for outcome-domain scores:

$$O_{mit} = \frac{1}{K_{mit}^{O}} \sum_{k \in \mathcal{K}_{mit}^{O}} Y_{kit}^{*}, K_{mit}^{O} \geq 1.$$

Available-indicator averaging allows the analysis to retain a larger number of country-year observations. This is useful because cross-country food system indicators often have uneven coverage across time, regions, and indicator types.

However, this approach can also create differences in measurement precision. A domain score based on one observed indicator may be less reliable than a domain score based on several observed indicators. For this reason, robustness tests are implemented using stricter data-availability thresholds. Table A4 summarizes the baseline and stricter missing-data rules used in the robustness analysis.

Table A4. Missing-data rules and robustness thresholds.

Rule	Description	Purpose
At least one observed indicator per domain	Baseline available-indicator averaging.	Maximizes country-year coverage.
At least two observed indicators per domain	Requires at least two non-missing indicators within a domain.	Tests whether results depend on sparsely measured domains.
At least four of six domains	Requires broader coverage across cognitive domains.	Tests whether results depend on incomplete cognitive profiles.

Source: Author's methodological framework.

Formally, the stricter domain rule can be written as

$$D_{dit}^{C} \text{ is observed only if } K_{dit}^{C} \geq 2.$$

The broader index-coverage rule can be written as

$$FSCCI_{it}^{EQ} \text{ is observed only if } \sum_{d \in \mathcal{D}^{C}} 1\left(D_{dit}^{C} \text{ is observed}\right) \geq 4.$$

where $1(\cdot)$ is an indicator function equal to 1 when the condition is true and 0 otherwise.

These robustness checks assess whether the empirical findings are sensitive to uneven indicator coverage across countries and years.

9. PCA-based index

Principal component analysis is used as a robustness check for the weighting structure of the FSCCI.

The baseline index gives equal weight to each of the six cognitive domains. PCA provides an alternative, data-driven weighting approach by extracting the dominant common component across the six domain scores.

Let the vector of cognitive-domain scores for country i in year t be

$$D_{it}^{C} = \begin{bmatrix} D_{it}^{sens} \\ D_{it}^{feed} \\ D_{it}^{frame} \\ D_{it}^{coord} \\ D_{it}^{admin} \\ D_{it}^{anti} \end{bmatrix}.$$

Before PCA is estimated, the domain scores are standardized:

$$Z_{dit} = \frac{D_{dit}^{C} - \bar{D}_{d}^{C}}{s_{d}},$$

where $\bar{D}_{d}^{C}$ is the sample mean of domain d, and s_{d} is the sample standard deviation of domain d.

The standardized domain vector is

$$Z_{it} = \begin{bmatrix} Z_{it}^{sens} \\ Z_{it}^{feed} \\ Z_{it}^{frame} \\ Z_{it}^{coord} \\ Z_{it}^{admin} \\ Z_{it}^{anti} \end{bmatrix}.$$

The first principal component is then calculated as

$$PC1_{it} = a_1 Z_{it}^{sens} + a_2 Z_{it}^{feed} + a_3 Z_{it}^{frame} + a_4 Z_{it}^{coord} + a_5 Z_{it}^{admin} + a_6 Z_{it}^{anti},$$

or, equivalently,

$$PC1_{it} = a' Z_{it},$$

where

$$a = [a_1 \quad a_2 \quad a_3 \quad a_4 \quad a_5 \quad a_6]'$$

is the vector of first-component loadings.

Because the sign of a principal component is arbitrary, $PC1_{it}$ is oriented so that it is positively correlated with the equal-weighted index:

$$corr\left(PC1_{it}, FSCCI_{it}^{EQ}\right) > 0.$$

The oriented first principal component is then rescaled to the 0–100 range:

$$FSCCI_{it}^{PCA} = 100 \times \frac{PC1_{it} - \min(PC1)}{\max(PC1) - \min(PC1)}.$$

The corresponding PCA-based cognitive failure index is

$$FSCFI_{it}^{PCA} = 100 - FSCCI_{it}^{PCA}.$$

The PCA-based index is not used as the main specification because its weights are sample-dependent and less transparent than equal weighting. Instead, it is used as a robustness check. If the equal-weighted and PCA-based indexes are strongly correlated, this supports the interpretation that the six cognitive domains capture a coherent latent construct.

10. Econometric models

10.1 Baseline two-way fixed-effects model

The baseline empirical model estimates the association between lagged food system cognitive capacity and subsequent transformation performance.

The preferred specification is a two-way fixed-effects model:

$$FSTPI_{it} = \beta_1 FSCCI_{i,t-1} + \mu_i + \tau_t + \varepsilon_{it}.$$

where $FSTPI_{it}$ is the FSTPI for country i in year t, $FSCCI_{i,t\text{-}1}$ is the lagged FSCCI, μ_i is a country fixed effect, τ_t is a year fixed effect, and ε_{it} is the error term.

The coefficient of interest is β_1. The expected sign is

$$\beta_1 > 0.$$

A positive β_1 indicates that countries with stronger cognitive capacity in the previous year tend to have stronger food systems transformation performance in the current year, conditional on country and year fixed effects.

Standard errors are clustered at the country level to allow for serial correlation and heteroskedasticity within countries over time.

The corresponding controlled specification is:

$$FSTPI_{it} = \beta_1 FSCCI_{i,t-1} + \gamma' X_{it} + \mu_i + \tau_t + \varepsilon_{it}$$

10.2 Outcome-specific models

To examine whether cognitive capacity is more strongly associated with some dimensions of transformation than others, the baseline specification is estimated separately for each outcome domain.

For each outcome domain $m \in D^O$, the model is

$$O_{mit} = \beta_1 FSCCI_{i,t-1} + \mu_i + \tau_t + \varepsilon_{mit}.$$

where O_{mit} is the score for outcome domain m, such as food security, diet quality, affordability, sustainability, resilience, or equity and livelihoods.

This specification identifies which transformation domains are most closely associated with cognitive capacity.

With time-varying controls, the outcome-specific model becomes:

$$O_{mit} = \beta_{1m} FSCCI_{i,t-1} + \gamma' X_{it} + \mu_i + \tau_t + \varepsilon_{mit}$$

10.3 Policy-presence interaction model

The policy-presence interaction model tests whether formal food system policy commitments are more strongly associated with outcomes when cognitive capacity is higher.

Let $Pathway_{it}$ denote the presence of a national food systems transformation pathway or equivalent policy commitment. The model is

$$Y_{it} = \beta_1 FSCCI_{i,t-1} + \beta_2 Pathway_{it} + \beta_3 \left(FSCCI_{i,t-1} \times Pathway_{it}\right) + \mu_i + \tau_t + \varepsilon_{it}.$$

The coefficient β_3 captures whether the association between policy presence and the outcome differs by the level of cognitive capacity.

A positive interaction coefficient,

$$\beta_3 > 0,$$

would suggest that national food systems transformation pathways are more strongly associated with improved outcomes in countries with stronger cognitive capacity.

This specification is motivated by the possibility that policy presence alone is insufficient. Policies may be more effective when systems have stronger information processing, feedback, coordination, and implementation capacity.

The controlled policy-interaction specification is:

$$Y_{it} = \beta_1 FSCCI_{i,t-1} + \beta_2 Pathway_{it} + \beta_3 FSCCI_{i,t-1} \times Pathway_{it} + \gamma' X_{it} + \mu_i + \tau_t + \varepsilon_{it}$$

10.4 Shock-moderation model

The shock-moderation model tests whether cognitive capacity buffers the adverse effects of food system shocks.

Let $Shock_{it}$ denote a shock variable, such as food price volatility, food supply variability, or disaster damages as a share of GDP. The model is

$$Y_{it} = \beta_1 FSCCI_{i,t-1} + \beta_2 Shock_{it} + \beta_3 \left(FSCCI_{i,t-1} \times Shock_{it}\right) + \mu_i + \tau_t + \varepsilon_{it}.$$

For positive transformation outcomes, the expected sign of the shock coefficient is

$$\beta_2 < 0.$$

This means that stronger shocks are expected to reduce transformation performance.

The expected sign of the interaction coefficient is

$$\beta_3 > 0.$$

A positive β_3 would indicate that cognitive capacity moderates, or buffers, the negative effect of shocks. In other words, food systems with stronger cognitive capacity may be better able to anticipate, absorb, and adapt to instability. The controlled specification is:

$$Y_{it} = \beta_1 \, FSCCI_{i,t-1} + \beta_2 \, Shock_{it} + \beta_3 \, FSCCI_{i,t-1} \times Shock_{it} + \gamma' X_{it} + \mu_i + \tau_t + \varepsilon_{it}$$

10.5 Region-year fixed-effects model

The region-year fixed-effects model accounts for region-specific shocks, trends, and policy environments.

The specification is

$$Y_{it} = \beta_1 FSCCI_{i,t-1} + \mu_i + \tau_{r(i)t} + \varepsilon_{it}.$$

where $\tau_{r(i)t}$ is a region-year fixed effect for the region r to which country i belongs.

This model compares countries within the same region and year, thereby controlling for common region-specific factors such as regional price shocks, climate conditions, trade disruptions, or policy trends.

The controlled region-year fixed-effects specification is:

$$Y_{it} = \beta_1 \, FSCCI_{i,t-1} + \gamma' X_{it} + \mu_i + \tau_{rt} + \varepsilon_{it}$$

10.6 Controlled model

The controlled model adds observable time-varying covariates to the baseline specification.

Let X_{it} denote a vector of time-varying controls. The model is

$$Y_{it} = \beta_1 \, FSCCI_{i,t-1} + \gamma' X_{it} + \mu_i + \tau_t + \varepsilon_{it}.$$

Candidate controls available in the FCI/FSCI export include agriculture's share of GDP, disaster damages as a share of GDP, food price volatility, unemployment, and underemployment. A variable is excluded from X_{it} whenever it is used to construct the FSCCI, FSCFI, FSTPI, or the specific outcome being modeled. Thus, disaster damages and food price volatility are included only in specifications where they do not create mechanical overlap with the regressor or dependent variable.

GDP per capita, conflict exposure, and climate vulnerability were not available in the uploaded FCI/FSCI export and require external data merges. Controlled models should be reported as sensitivity analyses with the exact covariate set, timing, sample, and missing-data rule stated for each specification.

The controlled model helps assess whether the estimated association between cognitive capacity and transformation performance is robust to observable structural conditions.

11. Cluster analysis

Cluster analysis is used to identify diagnostic profiles of food system cognitive capacity and cognitive failure. The purpose is descriptive rather than causal: clusters help characterize different types of cognitive-system weakness across countries.

Countries are clustered using the six cognitive-domain scores:

$$D_i^C = \begin{bmatrix} D_i^{sens} \\ D_i^{feed} \\ D_i^{frame} \\ D_i^{coord} \\ D_i^{admin} \\ D_i^{anti} \end{bmatrix}.$$

If clustering is conducted on country-year observations, the vector can be written as

$$D_{it}^C = \begin{bmatrix} D_{it}^{sens} \\ D_{it}^{feed} \\ D_{it}^{frame} \\ D_{it}^{coord} \\ D_{it}^{admin} \\ D_{it}^{anti} \end{bmatrix}.$$

Before clustering, domain scores should be standardized if the clustering algorithm is sensitive to scale. Since all domain scores are already measured on a 0–100 scale, standardization is not strictly required, but it may still be useful if domains differ substantially in variance.

Using k-means clustering, countries are assigned to C clusters by minimizing within-cluster variance:

$$\min_{\{C_1,\dots,C_C\}} \sum_{c=1}^{C} \sum_{i \in C_c} \| D_i^C - \bar{D}_c^C \|^2,$$

where C_c is cluster c, and $\bar{D}_c^C$ is the centroid of cluster c.

The implemented five-cluster model identifies diagnostic profiles such as:

Table A5 summarizes the diagnostic interpretation of the five-cluster solution.

Table A5. Diagnostic cognitive-capacity cluster profiles.

Cluster profile	Interpretation
High cognitive-capacity systems	Countries with relatively strong scores across most cognitive domains.
Policy-rich but coordination-constrained systems	Countries with formal policy commitments but weaker coordination, feedback, or implementation capacity.
Low-feedback and low-sensing systems	Countries with weak information flows, limited transparency, and weaker public accountability.
Sensing-strong but policy-framing-weak systems	Countries with some information capacity but weaker formal recognition of food systems transformation priorities.
Broad cognitive-failure systems	Countries with consistently low scores across multiple cognitive domains.

Source: Author's cluster analysis.

These clusters are intended to support diagnosis and interpretation. They should not be interpreted as causal categories. A country's cluster membership reflects similarity in observed cognitive-domain profiles, not proof of a specific causal mechanism.

12. Identification and causal interpretation

The empirical strategy is designed to estimate the association between food system cognitive capacity and food systems transformation performance. The models should be interpreted as providing evidence of structured empirical relationships, not definitive causal effects.

The baseline model is

$$FSTPI_{it} = \beta_1 FSCCI_{i,t-1} + \mu_i + \tau_t + \varepsilon_{it}.$$

This specification includes three features that strengthen the interpretation of the estimated association.

First, cognitive capacity is lagged by one year:

$$FSCCI_{i,t-1}.$$

Using a lagged explanatory variable reduces simultaneity concerns because cognitive capacity is measured before the outcome. This helps distinguish whether prior cognitive capacity is associated with subsequent transformation performance.

Second, the model includes country fixed effects:

$$\mu_i.$$

Country fixed effects control for time-invariant country characteristics, such as geography, long-standing institutional traditions, historical development patterns, agroecological conditions, or persistent cultural and political features.

Third, the model includes year fixed effects:

$$\tau_t.$$

Year fixed effects control for shocks and trends that affect all countries in a given year, such as global food price shocks, international policy attention, pandemics, or global economic conditions.

Despite these strengths, the model remains associational. A causal interpretation is limited by several potential threats. Table A6 summarizes the principal threats that limit causal interpretation.

Table A6. Threats to identification and causal interpretation.

Threat	Explanation
Reverse causality	Stronger transformation outcomes may improve governance, data systems, or policy capacity, rather than only the reverse.
Time-varying omitted variables	Unobserved factors that change over time, such as donor support, conflict, political instability, or fiscal capacity, may affect both cognitive capacity and outcomes.
Measurement error	Cognitive capacity is a latent construct measured through imperfect proxies.
Uneven indicator coverage	Some countries and years have more complete data than others, which may affect comparability.
Policy endogeneity	Countries may adopt food system policies in response to worsening outcomes, making policy variables endogenous.
Unobserved implementation quality	Formal policy presence may not reflect actual administrative effort, enforcement, or institutional learning.
Differences in statistical capacity	Countries with stronger statistical systems may appear to have stronger cognitive capacity partly because they measure and report more effectively.

Source: Author's methodological framework.

The coefficient

$$\hat{\beta}_1$$

therefore should be interpreted as the estimated within-country association between lagged cognitive capacity and transformation performance, after accounting for common year shocks.

A stronger causal design would require additional strategies, such as event studies, difference-in-differences, instrumental variables, synthetic control methods, or subnational validation.

For example, if a major policy reform or institutional innovation occurred in some countries but not others, an event-study specification could be used:

$$Y_{it} = \sum_{\ell \neq -1} \delta_\ell \, 1(t - T_i = \ell) + \mu_i + \tau_t + \varepsilon_{it},$$

where T_i is the reform year for country i, and δ_l traces the outcome path before and after the reform.

Similarly, a difference-in-differences model could be written as

$$Y_{it} = \delta(Treat_i \times Post_t) + \mu_i + \tau_t + \varepsilon_{it},$$

where $Treat_i$ identifies countries exposed to a reform that enhances cognitive capacity, and $Post_t$ identifies the postreform period.

These designs would provide stronger evidence if the identifying assumptions are plausible. In the current analysis, however, the results should be presented as evidence consistent with the cognitive failure hypothesis, rather than as conclusive causal proof.

13. Limitations

Several limitations should be acknowledged when interpreting the FSCCI, the FSCFI, and the associated econometric results.

First, cognitive capacity is a latent construct. The FSCCI measures observable proxies of cognitive capacity, not cognition directly. Indicators such as public access to information, government effectiveness, accountability, social capital, and policy recognition capture important dimensions of system cognition, but they cannot fully measure processes such as institutional memory, bureaucratic learning, deliberation quality, or problem interpretation.

Second, indicator availability varies across countries, years, and domains. Some country-years have more complete information than others. This may affect cross-country comparability, especially for countries with weaker statistical systems, small states, fragile states, or countries with limited reporting capacity.

Third, the index combines different types of indicators. Some indicators are continuous, while others are binary or ordinal. This means that measurement precision differs across indicators. For example, a continuous governance score may capture gradual changes over time, whereas a binary policy indicator records only the presence or absence of a formal commitment.

Fourth, the normalization procedure is sample-dependent. Min–max normalization scales each indicator using the observed minimum and maximum values in the analytical sample:

$$X^*_{kit} = 100 \times \frac{X_{kit} - \min(X_k)}{\max(X_k) - \min(X_k)}.$$

As a result, normalized scores depend on the sample period and country coverage. Adding new countries, years, or updated observations could change the minimum and maximum values and therefore affect normalized scores.

Fifth, the interdependence-adjusted index depends on the structure of the interaction matrix. The adjusted score is calculated as

$$\tilde{x}_{jit} = \lambda x_{jit} + (1-\lambda) \sum_{k \in \mathcal{N}_{jit}} \widetilde{w}_{jk,it}\, x_{kit}.$$

This means that results may be sensitive to the assumed relationships among indicators, the mapping between interaction-matrix labels and FCI/FSCI indicators, and the selected value of the own-indicator weight λ.

Sixth, the econometric models are associational. The baseline specification,

$$FSTPI_{it} = \beta_1 FSCCI_{i,t-1} + \mu_i + \tau_t + \varepsilon_{it},$$

controls for country fixed effects and year fixed effects, but it does not fully eliminate concerns about time-varying omitted variables, reverse causality, policy endogeneity, or measurement error.

The controlled counterpart,

$$FSTPI_{it} = \beta_1 FSCCI_{i,t-1} + \gamma' X_{it} + \mu_i + \tau_t + \varepsilon_{it}$$

addresses only observed time-varying covariates and remains subject to unobserved confounding, measurement error, reverse causality, and possible over-control.

Seventh, policy presence is not the same as policy implementation. Formal recognition of a food system pathway, right to food, or food environment policy may not reflect enforcement quality, administrative follow-through, fiscal commitment, or institutional learning.

Finally, the analysis is conducted at the national level. National indicators may mask subnational differences in governance capacity, food environments, ecological conditions, market access, and vulnerability to shocks. Future work could strengthen the analysis by incorporating subnational data, case study validation, external controls, and stronger causal research designs.

14. Summary

The revised empirical approach consists of six linked steps.

First, all indicators are normalized to a common 0–100 scale with consistent directionality:

$$0 \le X^*_{kit} \le 100.$$

For cognitive-capacity indicators, higher values indicate stronger cognitive capacity. For transformation-outcome indicators, higher values indicate stronger food systems transformation performance.

Second, normalized cognitive indicators are grouped into six cognitive domains:

$$\mathcal{D}^C = \{\text{sensing,feedback,framing,coordination,administration,anticipation}\}.$$

Each domain score is calculated as an available-indicator average:

$$D^C_{dit} = \frac{1}{K^C_{dit}} \sum_{k \in \mathcal{K}^C_{dit}} X^*_{kit}.$$

Third, the equal-weighted FSCCI is calculated as

$$FSCCI^{EQ}_{it} = \frac{1}{6} \sum_{d \in \mathcal{D}^C} D^C_{dit}.$$

The corresponding FSCFI is

$$FSCFI^{EQ}_{it} = 100 - FSCCI^{EQ}_{it}.$$

Fourth, robustness versions of the index are constructed. The PCA-based index uses the first principal component of the standardized cognitive-domain scores:

$$PC1_{it} = a' Z_{it},$$

which is then oriented and rescaled to the 0–100 range:

$$FSCCI^{PCA}_{it} = 100 \times \frac{PC1_{it} - \min(PC1)}{\max(PC1) - \min(PC1)}.$$

The interdependence-adjusted version incorporates the weighted food system neighborhood of each indicator:

$$\tilde{x}_{jit} = \lambda x_{jit} + (1 - \lambda) \sum_{k \in \mathcal{N}_{jit}} \widetilde{w}_{jk,it}\, x_{kit}.$$

The adjusted domain score is

$$\widetilde{D}^C_{dit} = \frac{1}{K^C_{dit}} \sum_{k \in \mathcal{K}^C_{dit}} \tilde{x}_{kit},$$

and the interdependence-adjusted cognitive-capacity index is

$$FSCCI^{INT}_{it} = \frac{1}{6} \sum_{d \in \mathcal{D}^C} \widetilde{D}^C_{dit}.$$

The corresponding failure index is

$$FSCFI_{it}^{INT} = 100 - FSCCI_{it}^{INT}.$$

Fifth, the FSTPI is constructed separately from the cognitive-capacity index. Outcome indicators are grouped into six transformation domains:

$$\mathcal{D}^O = \{\text{food security,diet quality,affordability,sustainability,resilience,equity and livelihoods}\}.$$

The outcome-domain score is

$$O_{mit} = \frac{1}{K_{mit}^O} \sum_{k \in \mathcal{K}_{mit}^O} Y_{kit}^*,$$

and the aggregate transformation-performance index is

$$FSTPI_{it} = \frac{1}{6} \sum_{m \in \mathcal{D}^O} O_{mit}.$$

Sixth, the empirical relationship between cognitive capacity and transformation performance is estimated using fixed-effects models. The baseline specification is

$$FSTPI_{it} = \beta_1 FSCCI_{i,t-1} + \mu_i + \tau_t + \varepsilon_{it}.$$

The main coefficient of interest is

$$\beta_1.$$

A positive estimate,

$$\hat{\beta}_1 > 0,$$

is interpreted as evidence that stronger lagged food system cognitive capacity is associated with stronger subsequent transformation performance.

The controlled sensitivity specification is:

$\mathrm{FSTPI}_{it} = \beta_1\ \mathrm{FSCCI}_{i,t\text{-}1} + \gamma'\ X_{it} + \mu_i + \tau_t + \varepsilon_{it}.$

Here, X_it contains only pre-specified time-varying covariates that are not components of the cognitive-capacity index or the modeled outcome.

The implemented results suggest that food system cognitive capacity is measurable and policy relevant. Countries with stronger cognitive capacity tend to show better transformation performance, especially in resilience and sustainability. The interdependence-adjusted results further support the argument that cognitive failure is a systems property: weaknesses in information processing, coordination, feedback, and adaptive capacity can propagate through interconnected food system domains.

Overall, the framework provides a structured way to diagnose not only whether food systems are transforming, but also whether they possess the cognitive capacity required to understand problems, coordinate responses, learn from feedback, and adapt under uncertainty.

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