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Sustainability Profiles of Peruvian Dairy Cattle Producers Using National Survey Data: A Frame-Aware MESMIS-Informed Assessment, 2021–2024

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Abstract

National dairy sustainability monitoring requires indicators that are scientifically defensible, policy-relevant, and feasible to construct from recurrent agricultural surveys. The aim of this study was to construct, interpret, and evaluate a national, survey-weighted, frame-aware, MESMIS-informed monitoring profile for Peruvian dairy cattle producers using ENA 2021–2024 microdata. The Peruvian National Agricultural Survey (Encuesta Nacional Agropecuaria, ENA) was explicitly treated as a source of proxy-based sustainability monitoring rather than as a complete farm sustainability assessment. Using survey design variables and harmonized items on livestock, markets, producer capacity, and resource management, the analysis constructed survey-weighted formative profiles for nationally monitored dairy cattle producer units. The analytical sample comprised 42,331 agricultural producer units selected based on complete interview status, reported livestock activity, and harmonized evidence of dairy cattle activity. Because ENA documentation indicates a sampling-frame transition in 2023, the 2021–2022 and 2023–2024 rounds were treated as separate sampling-frame regimes. Indicators were scaled to 0–1 formative profiles, with explicit checks for missingness, indicator availability, exclusion of derivative outputs, exclusion of producer age, minimum-availability thresholds, and sampling-regime-specific scaling. The median indicator availability was 12 of 14 economic and productive indicators, five of five social access and capacity indicators, and eight of eight environmental and resource-management indicators. Survey-weighted descriptive estimates and adjusted within-regime contrasts showed that the strongest signal was a lower social access and capacity profile in 2022 than in 2021, mainly associated with lower agricultural information use, livestock training, and technical assistance. Within the 2023–2024 sampling-frame regime, the main adjusted profiles were statistically stable. The results show that ENA can support a reproducible national monitoring baseline, provided that the resulting profiles are interpreted as proxy-based formative summaries constrained by survey coverage rather than as direct environmental performance scores, causal trends, or complete sustainability measures.



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1. Introduction

Assessing the sustainability of dairy systems requires a systems perspective because farm performance emerges from interactions among herd resources, milk production, market participation, access to extension services, producer organization, pasture management, and environmental conditions. In Peru, dairy cattle production includes smallholder, mixed crop–livestock, and more market-oriented systems that differ substantially in land availability, herd size, productivity, input use, access to services, and resource-management practices [1–5]. This heterogeneity creates a need for nationally comparable evidence that extends beyond production indicators and captures multiple dimensions relevant to the sustainability of dairy farming systems.

Generating such evidence at the national level remains methodologically challenging. Detailed farm sustainability assessments generally require primary information on economic performance, labor conditions, household well-being, soil and water management, greenhouse gas emissions, biodiversity, animal welfare, and institutional participation. These data are rarely consistently available across recurrent national agricultural surveys. The central problem is therefore how official survey microdata can be used for multidimensional sustainability monitoring without being interpreted as a complete farm-level sustainability assessment.

Several frameworks provide complementary approaches to agricultural sustainability assessment. Life Cycle Assessment (LCA) quantifies environmental impacts associated with products and production processes across defined life cycle boundaries, but it requires detailed inventory data and does not, by itself, provide comprehensive coverage of social, institutional, and producer-capacity dimensions. The Sustainability Assessment of Food and Agriculture Systems (SAFA) framework offers broad coverage of environmental integrity, economic resilience, social well-being, and governance, but its full implementation requires information that is not routinely collected in general agricultural surveys. The IDEA method (Indicateurs de Durabilité des Exploitations Agricoles) provides an integrated farm-level diagnostic through economic, agroecological, and socio-territorial indicators, although it also depends on detailed holding-level information and context-specific assessment procedures [6–10].

The Framework for the Evaluation of Natural Resource Management Systems Incorporating Sustainability Indicators (MESMIS) offers a flexible and context-sensitive alternative. MESMIS links system characteristics and critical points to attributes such as productivity, stability, reliability, resilience, adaptability, equity, and self-reliance, and organizes assessment as an iterative cycle of system characterization, indicator selection, measurement, integration, and feedback [11–14]. Its main strengths are its multidimensional perspective, adaptability to different agricultural systems, and explicit connection between indicators and system-level sustainability attributes. However, conventional MESMIS applications are generally participatory, locally grounded, and based on detailed primary information. Consequently, applying MESMIS to secondary national survey data requires a transparent adaptation rather than a claim that the complete participatory protocol has been implemented.

In this study, MESMIS is therefore used as an organizing framework for defining sustainability-relevant domains, linking indicators to conceptual attributes, identifying data limitations, and structuring interpretation and feedback. The resulting measures

are treated as proxy-based formative profiles rather than direct measurements of comprehensive farm sustainability. Indicator definitions, source variables, units, favorable direction, denominator restrictions, missingness, normalization, and aggregation rules must consequently be made explicit. Domains that are not adequately observed in the survey—including direct greenhouse gas emissions, nutrient balances, soil quality, water-use efficiency, biodiversity, animal welfare, labor conditions, access to health services, and broader dimensions of human capital—are acknowledged as measurement gaps rather than estimated through unsupported assumptions.

This distinction is also important for the statistical construction of profiles. Reflective measurement models and internal-consistency statistics are appropriate when observed variables are interchangeable manifestations of a common latent construct. Sustainability indicators are often formative because they represent complementary system characteristics that may contribute independently to a broader profile and therefore need not be strongly correlated [15,16]. In the present study, productive and market indicators, social access and producer-capacity indicators, and environmental and resource-management indicators are interpreted as complementary components. High internal consistency is therefore neither assumed nor used as the principal criterion of measurement quality; transparency, coverage, sensitivity, and substantive interpretability are emphasized instead.

The Peruvian National Agricultural Survey (Encuesta Nacional Agropecuaria, ENA) is an official, recurrent survey that provides nationally representative information on agricultural production units, livestock activities, market participation, producer characteristics, technical assistance, training, organization, and selected resource-management practices [17–21]. Its repeated cross-sectional design makes it useful for national monitoring, but does not allow changes within the same farms to be identified over time. In addition, official ENA and Ministry of Agricultural Development and Irrigation (MIDAGRI) documentation, together with survey design diagnostics, indicate a relevant transition in the sampling frame in 2023. The 2021–2022 and 2023–2024 rounds are therefore treated as separate sampling-frame regimes, and comparisons across the 2022–2023 boundary are not interpreted as substantive temporal change [22–27].

The 2021–2024 period was selected because these survey rounds provide the harmonized dairy cattle modules, source variables, and survey design information required to construct the complete set of indicators used in this study. Extending the series to earlier years would require an additional audit of questionnaire content, variable definitions, module routing, sampling frames, and harmonization rules. The four-year period is therefore suitable for establishing a reproducible monitoring baseline and for examining comparisons within the identified sampling-frame regimes, but it is not sufficient for inferring long-term structural trends or sustainability transitions.

Previous MESMIS applications in Latin America have predominantly focused on farms, communities, production systems, or regional case studies using detailed and frequent participatory information. National applications based on recurrent, probability-based agricultural survey microdata remain limited. This study addresses that methodological gap by operationalizing a frame-aware, MESMIS-informed monitoring protocol for Peruvian dairy cattle producers while explicitly distinguishing proxy indicators from comprehensive sustainability measures and formative profiles from reflective scales.

Accordingly, the objective of this study was to construct, interpret, and evaluate a national, survey-weighted, frame-aware, MESMIS-informed monitoring profile for Peruvian dairy cattle producers using ENA 2021–2024 microdata. Specifically, the analysis aimed to: (i) characterize the study population and document comparable temporal patterns within the 2021–2022 and 2023–2024 sampling-frame regimes; (ii) identify the individual indicators underlying the economic, social access and capacity, and environmental

and resource-management profiles; and (iii) assess the robustness of the findings to survey weighting, missing-data requirements, indicator availability, indicator inclusion, and scaling choices.

2. Materials and Methods

2.1. Data Source, Analytical Unit, and Study Population

This study used microdata from the 2021, 2022, 2023, and 2024 rounds of the Peruvian National Agricultural Survey (Encuesta Nacional Agropecuaria, ENA). ENA is an official, repeated cross-sectional survey designed to generate agricultural sector statistics and provide evidence for monitoring agricultural policies and programs [22,23,26]. The survey does not follow the same agricultural production units over time; therefore, annual observations represent independent cross-sections rather than longitudinal farm trajectories. The public-use ENA files used in this study do not provide a stable longitudinal farm identifier that would allow the same agricultural producer unit to be linked across survey years. Therefore, the analytical sample should be interpreted as annual producer-unit observations from independent cross-sections, not as a panel of unique dairy farms followed over time.

The analytical unit was the agricultural producer unit. The target population for this study comprised surveyed agricultural production units with a valid, completed interview, reported livestock activity, and harmonized evidence of dairy cattle activity, operationally defined as the presence of at least one cow in milk. This criterion was applied consistently across the four survey rounds. The eligibility sequence and its correspondence with the harmonized ENA variables are documented in Table A1.

The final analytical sample comprised 42,331 agricultural producer units: 8247 in 2021, 7819 in 2022, 11,789 in 2023, and 14,476 in 2024. Inclusion in the analytical sample did not require complete milk-volume records because production, allocation, and derivative-output variables were affected by questionnaire routing, structural non-applicability, and item nonresponse. Milk-volume information was available for 4863 units in 2021, 4442 in 2022, 6888 in 2023, and 8540 in 2024.

The analysis used harmonized information from ENA modules covering livestock production, milk allocation and commercialization, agricultural producer and household characteristics, technical assistance, livestock training, agricultural information use, producer organization, pasture management, irrigation and resource management, forest area, and crop or livestock residue management. Each constructed indicator is linked to its original ENA question, source variable, harmonized variable, unit of measurement, denominator, construction rule, year of availability, and missing-data condition in Appendix A Tables A1, A2 and A8.

Because the study used anonymized public-use secondary microdata and did not involve direct interaction with producers, no new primary data were collected. Table 1 summarizes the analytical sample and milk-volume availability by year.

Table 1. Analytical sample and milk-volume availability by year.

Year	Sampling-Frame Regime	Final Analytical Sample, N	Milk-Volume Information Available, N	Availability, %
2021	2021–2022	8247	4863	58.97
2022	2021–2022	7819	4442	56.81
2023	2023–2024	11,789	6888	58.43
2024	2023–2024	14,476	8540	58.99
Total		42,331	24,733	58.43

Note: Milk-volume availability refers to non-missing information for the harmonized milk-production and allocation variables. The analytical sample was defined by dairy cattle activity rather than by complete milk-volume records.

2.2. Study System, Analytical Boundaries, and MESMIS-Informed Adaptation

The study system was defined as the nationally monitored population of Peruvian agricultural producer units that reported dairy cattle activity in ENA 2021–2024. The analytical boundary was the agricultural producer unit and the productive, market, producer-capacity, organizational, pasture management, and resource-management characteristics observed in the survey.

The spatial scope was national, and the temporal scope comprised the four annual ENA cross-sections from 2021 to 2024. The inferential scope was limited to survey-weighted national monitoring and within-sampling-frame comparisons. The study did not define a product life cycle boundary or estimate environmental footprints, greenhouse gas emissions, profitability, household welfare, or causal intervention effects.

MESMIS was used as an organizing framework rather than as a claim that the full participatory MESMIS protocol had been implemented. Its six-step cycle was adapted to the possibilities and limitations of secondary national survey data. System characterization and critical-point identification were informed by the dairy-system literature, ENA questionnaire coverage, and observed management constraints rather than by participatory workshops with producers.

The critical points represented in the monitoring framework were: (i) productive capacity and milk-use diversification; (ii) market participation and household milk allocation; (iii) access to technical assistance, training, agricultural information, and producer organization; and (iv) pasture and resource-management practices. The sampling-frame transition in 2023 was treated separately as a survey design constraint rather than as a sustainability critical point of the dairy production system. Table 2 summarizes the operational adaptation of the six-step MESMIS cycle to ENA microdata.

Table 2. Operational adaptation of the MESMIS cycle to ENA microdata.

MESMIS Step	Application in this Study	Constraint or Methodological Decision
1. Characterize the system	Peruvian agricultural producer units reporting dairy cattle activity in ENA 2021–2024; the analytical unit is the agricultural producer unit.	ENA is a repeated cross-section; estimates describe national producer profiles rather than changes within the same farms.
2. Identify critical points	Productive capacity, milk allocation and market participation, access to services and information, producer organization, and pasture/resource management.	Critical points were identified analytically from the literature, questionnaire coverage, and observed constraints rather than through a participatory MESMIS workshop.
3. Select indicators	ENA variables were retained when they were conceptually linked to a MESMIS attribute, directionally interpretable, reproducible across years, and sufficiently available.	Domains not adequately observed in ENA were identified as measurement gaps and were not estimated under unsupported assumptions.
4. Measure indicators	Original questions and source variables were harmonized across years; units, denominators, favorable directions, missingness rules, and scoring procedures were defined explicitly.	Question-level and variable-level traceability is provided in the Appendix A.
5. Integrate results	Indicator scores were aggregated into equal-weight formative profiles for economic and productive conditions, social access and capacity, and environmental and resource management.	The profiles are formative summaries, not reflective latent scales. The overall profile is secondary and compensatory.
6. Conclusions and feedback	Results were used to identify monitored constraints, interpretation limits, policy-relevant signals, and priorities for improving future ENA modules.	Recommendations are proportional to the observational and proxy-based nature of the data and are not interpreted as causal intervention effects.

2.3. Sampling-Frame Regimes

The four survey rounds were divided into two analytical sampling-frame regimes: 2021–2022 and 2023–2024. The ENA 2023 technical documentation reports coordination with the Ministry of Agricultural Development and Irrigation (MIDAGRI) in the preparation of the master area sampling frame and states that the sampling frame used for sample selection was provided in March 2023 [22,24,26].

The distinction between the two regimes was also supported by survey design and coverage diagnostics, including the annual analytical sample size, weighted population totals, the number of primary sampling units, the number of strata, regional coverage, and milk-volume availability. These diagnostics are reported in Table A7, while the annual survey design specifications are summarized in Appendix A Table A7.

Survey-weighted descriptive profiles were estimated separately for each year. Inferential contrasts were restricted to comparisons within the same sampling-frame regime: 2021 versus 2022 and 2023 versus 2024. Differences across the 2022–2023 boundary were interpreted as potentially affected by changes in frame composition and survey coverage and were therefore not treated as evidence of substantive sustainability change. The four survey rounds were not modeled as a single continuous temporal trend.

2.4. Indicator Definition, Classification, and Direction

The analytical pipeline distinguished five levels of information:

- ENA source question and original variable: The questionnaire item and variable contained in the annual public-use microdata;
- Harmonized variable: The cross-year variable created after reconciling coding, labels, questionnaire routing, and year-specific availability;
- Constructed indicator: The producer-level measure derived from one or more harmonized variables;
- Standardized indicator score: The indicator transformed to a common 0–1 scale, with higher values representing the prespecified favorable direction;
- Formative profile: The arithmetic combination of available standardized indicators within a monitoring domain.

Variable harmonization was conducted before indicator construction. First, the annual ENA questionnaires, data dictionaries, variable labels, and coding schemes for 2021, 2022, 2023, and 2024 were reviewed. Second, equivalent source questions and variables were identified across survey rounds. Third, year-specific differences in coding, response categories, labels, units, questionnaire routing, and module availability were reconciled. Fourth, harmonized variables were constructed using common denominators, reference periods, and missing-data rules. Fifth, each harmonized variable was checked for year availability, structural non-applicability, item nonresponse, and consistency with the intended indicator definition. The full traceability from ENA source questions and original variables to harmonized variables, constructed indicators, units, denominators, construction rules, and missing-data conditions is reported in Appendix A Tables A1, A2 and A8.

Indicators were selected when they met four criteria: conceptual relevance to a MESMIS sustainability attribute; reproducible construction from harmonized ENA variables; an interpretable favorable direction; and sufficient data availability within at least one sampling-frame regime. Indicators were organized into three monitoring profiles: economic and productive conditions, social access and capacity, and environmental and resource management. The profile names describe the domains observed in ENA and should not be interpreted as complete measurements of economic, social, or environmental sustainability. ENA provides limited or no direct information on farm profitability, production costs, labor conditions, access to health services, multidimensional human capital,

greenhouse gas emissions, nutrient balances, soil quality, water-use efficiency, biodiversity, animal welfare, energy use, or transport-related environmental impacts.

Production and milk-allocation variables were interpreted as indicators of productive capacity, market participation, household use, or adaptability rather than as sufficient measures of sustainability. Resource-related indicators were interpreted as management and land-use proxies rather than as direct measures of environmental performance. Producer age was included only as an imperfect proxy for accumulated production experience and was examined through an exclusion sensitivity analysis. Table 3 summarizes the selected indicators, monitoring profiles, MESMIS attributes, and favorable directions used for profile construction.

Table 3. MESMIS-informed indicator framework.

Indicator	Type	Monitoring Profile	MESMIS Attribute	Favorable Direction
Total milk production	Continuous	Economic and productive	Productivity	Higher
Milk sold	Continuous		Productivity	Higher
Share of milk sold	Continuous		Self-reliance	Higher
Milk for household consumption	Continuous		Equity	Higher
Share for self-consumption	Continuous		Equity	Higher
Milk for derivatives	Continuous		Adaptability	Higher
Share processed into derivatives	Continuous		Adaptability	Higher
Cows in milk	Continuous/count		Productivity	Higher
Milk per cow	Continuous		Productivity	Higher
Bovine mortality	Continuous/count		Stability	Lower
Herd replacement	Continuous		Reliability	Higher
Milk-use diversification	Continuous/count		Adaptability	Higher
Certified semen or embryos	Binary		Adaptability	Higher
Derivative output	Continuous		Adaptability	Higher
Livestock training	Binary	Social access and capacity	Adaptability	Higher
Technical assistance	Binary		Adaptability	Higher
Agricultural information use	Binary		Adaptability	Higher
Producer experience proxy	Continuous		Reliability	Higher
Organization participation intensity	Continuous/count		Self-reliance	Higher
Milk per hectare	Continuous	Environmental and resource management	Productivity	Higher
Managed natural pasture area	Continuous		Stability	Higher
Pasture closure	Binary		Resilience	Higher
Pasture reseeding	Binary		Resilience	Higher
Forage within natural pasture	Binary		Resilience	Higher
Silvopastoral system	Binary		Resilience	Higher
Unmanaged natural pasture area	Continuous		Resilience	Lower
Forest area	Continuous		Resilience	Higher

Note: “Favorable direction” indicates the direction adopted for profile construction and does not imply that an indicator is independently sufficient to establish sustainability. Exact questionnaire codes, original variables, harmonized variables, units, denominators, construction rules, year availability, missingness conditions, and conceptual justifications are provided in Appendix A Tables A1, A2 and A8.

2.5. Missing Data and Formative Profile Construction

Missingness was evaluated before profile construction [28]. The analysis distinguished among item nonresponse, structural missingness caused by questionnaire routing, and non-applicability to the producer unit. Indicators were calculated only for their conceptually relevant denominators, and structurally inapplicable responses were not automatically recoded as zero.

Milk-volume variables were available for 58.97% of the analytical sample in 2021, 56.81% in 2022, 58.43% in 2023, and 58.99% in 2024. The median number of available indicators per producer unit was 12 of 14 economic and productive indicators, 5 of 5 social access and capacity indicators, and 8 of 8 environmental and resource-management indicators. Indicator-level missingness by year is reported in Table A2, and domain-level availability is reported in Table A4.

A complete-case analysis requiring all 27 indicators to be observed simultaneously was not feasible because some optional and derived variables, particularly derivative output, exhibited extensive structural missingness. No single-value imputation was used to replace missing indicators. Instead, primary profiles were calculated from the available indicators within each domain, and the robustness of this decision was evaluated using explicit minimum-availability thresholds.

To place indicators on a common scale and reduce the influence of extreme observations, valid indicator values were bounded at the pooled 1st and 99th percentiles. Let x_{ik} denote the observed value of indicator k for producer unit i , and let L_k and U_k denote the pooled 1st and 99th percentile bounds, respectively. The bounded value x_{ik}^b was defined as:

$$x_{ik}^b = \min[\max(x_{ik}, L_k), U_k] \quad (1)$$

For indicators for which higher observed values represented more favorable conditions, the positive-direction standardized score $s_{ik}^{(+)}$ was calculated as:

$$s_{ik}^{(+)} = \frac{x_{ik}^b - L_k}{U_k - L_k} \quad (2)$$

For reverse-direction indicators, where lower observed values represented more favorable conditions, the reverse-direction standardized score $s_{ik}^{(-)}$ was calculated as:

$$s_{ik}^{(-)} = 1 - \left[\frac{x_{ik}^b - L_k}{U_k - L_k} \right] \quad (3)$$

The final directed standardized score s_{ik} was assigned as $s_{ik}^{(+)}$ for higher-is-better indicators and as $s_{ik}^{(-)}$ for lower-is-better indicators. Scores were calculated only when $U_k > L_k$. When $U_k \leq L_k$, the corresponding score was treated as missing because the indicator had no valid variation within the scaling reference. Accordingly, valid standardized scores ranged from 0 to 1, with higher values indicating more favorable conditions in the prespecified direction. Binary indicators retained their 0–1 interpretation whenever their lower and upper bounds were 0 and 1.

Let K_{ij} denote the set of non-missing directed standardized indicators available for producer unit i in monitoring profile j , and let $m_{ij} = |K_{ij}|$. The formative profile D_{ij} was calculated as the arithmetic mean of the available standardized indicator scores:

$$D_{ij} = \frac{1}{m_{ij}} \sum_{k \in K_{ij}} s_{ik} \quad (4)$$

Equal indicator weights were used as a transparent baseline because no nationally validated stakeholder-derived weights were available [15]. Equal weighting does not imply that all indicators are substantively equivalent; rather, it avoids imposing unsupported differential weights. The overall profile was calculated as the arithmetic mean of the available domain profiles and was treated as a secondary, compensatory summary. Interpretation emphasized domain-level and indicator-level results.

Because the profiles were formative, measurement quality was evaluated using conceptual transparency, indicator traceability, data coverage, sensitivity, and interpretability rather than solely on internal-consistency coefficients.

Sensitivity analyses assessed the effects of: (i) requiring at least 50% or 70% indicator availability within each profile; (ii) excluding derivative output; (iii) excluding producer age; (iv) excluding the social access and capacity profile from the overall summary; and (v) using sampling-regime-specific rather than pooled 1st–99th percentile scaling. All sensitivity estimates and confidence intervals were generated using the ENA survey design. Table A5 reports the estimates, and Appendix A Table A5 explains the rationale and interpretation of each sensitivity scenario.

2.6. Survey-Weighted Estimation

Survey-weighted means and 95% confidence intervals were estimated using Stata/MP 16 and the survey design information available for each ENA round [29,30]. The survey settings incorporated the annual expansion factor as the probability weight, along with the corresponding strata and primary sampling unit identifiers. Singleton strata were handled using Stata's singleunit (scaled) adjustment. Variance estimates were design-based.

Descriptive estimates were produced separately for each survey year. Annual estimates were retained for visual and descriptive monitoring, but statistical contrasts were limited to years belonging to the same sampling-frame regime.

Within-regime adjusted contrasts were estimated using survey-weighted linear regression models. Separate models compared 2022 with 2021 and 2024 with 2023. Models included herd stock, land area, producer education, and regional fixed effects as adjustment variables. Variables that formed part of the outcome profile, including technical assistance and milk-commercialization indicators, were not included as covariates because doing so would condition on components of the outcome.

Regression coefficients were interpreted as adjusted descriptive differences between annual cross-sections within the same sampling-frame regime. They were not interpreted as causal year effects or as evidence of changes within the same agricultural producer units.

Python 3.11 (pandas, matplotlib, and seaborn) was used to harmonize variables, construct indicators, format exported statistical outputs and generate figures from the survey-weighted estimates. Statistical estimates, standard errors, confidence intervals, and sensitivity analyses were generated using the declared ENA survey design in Stata/MP 16.

3. Results

3.1. Frame-Aware Formative Profiles

Table 4 and Figure 1 presents the survey-weighted formative profiles for each ENA round. Comparisons were restricted to annual cross-sections within the same sampling-frame regime: 2021 versus 2022 and 2023 versus 2024. Differences across the sampling-frame boundary were not interpreted as substantive temporal change.

The economic and productive profile showed limited variation within both sampling-frame regimes. It was estimated at 0.144 [0.139, 0.149] in 2021 and 0.141 [0.136, 0.147] in 2022. The corresponding estimates were 0.134 [0.124, 0.144] in 2023 and 0.136 [0.129, 0.142] in 2024.

The largest within-regime difference occurred in the social access and capacity profile, which was lower in 2022 (0.274 [0.267, 0.280]) than in 2021 (0.306 [0.300, 0.311]). Within the 2023–2024 regime, the estimates were similar: 0.296 [0.286, 0.306] in 2023 and 0.302 [0.295, 0.309] in 2024.

Table 4. Frame-aware formative profiles by year.

Monitoring Profile	2021	2022	2023	2024
Economic and productive profile	0.144 [0.139, 0.149]	0.141 [0.136, 0.147]	0.134 [0.124, 0.144]	0.136 [0.129, 0.142]
Social access and capacity profile	0.306 [0.300, 0.311]	0.274 [0.267, 0.280]	0.296 [0.286, 0.306]	0.302 [0.295, 0.309]
Environmental and resource-management profile	0.163 [0.159, 0.167]	0.168 [0.164, 0.172]	0.170 [0.163, 0.177]	0.164 [0.159, 0.169]
Overall formative profile (secondary)	0.204 [0.201, 0.207]	0.194 [0.191, 0.198]	0.200 [0.194, 0.206]	0.201 [0.197, 0.204]
Overall profile excluding social access and capacity (sensitivity)	0.153 [0.150, 0.157]	0.155 [0.151, 0.158]	0.152 [0.146, 0.158]	0.150 [0.145, 0.154]

Note: Values are survey-weighted formative scores on a 0–1 scale. Values in brackets are 95% design-based confidence intervals. Higher values indicate more favorable conditions according to the prespecified indicator directions reported in Table 3. Comparisons across the 2022–2023 sampling-frame boundary should not be interpreted as substantive temporal change.

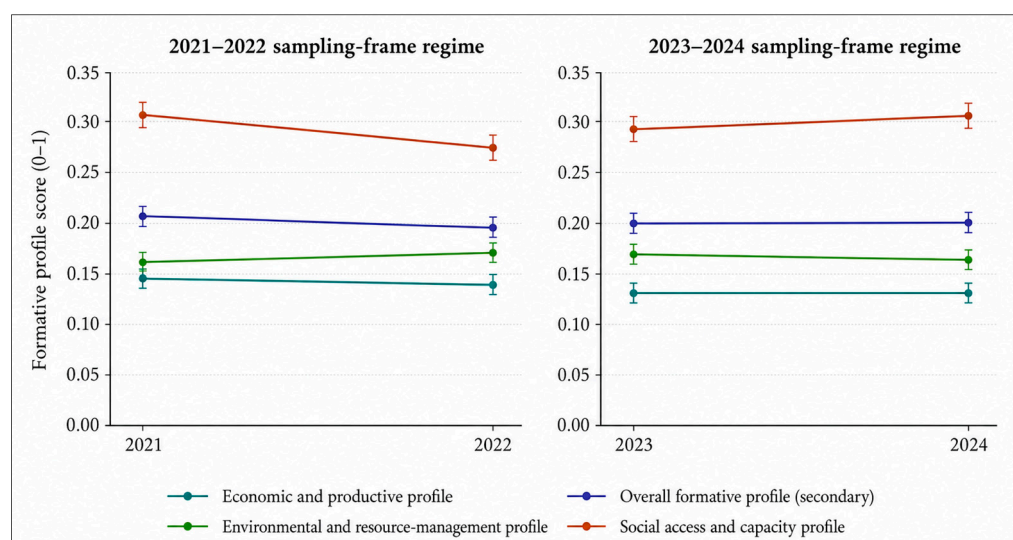


Figure 1. Survey-weighted formative profiles of Peruvian dairy cattle producers by sampling-frame regime. The panels distinguish the 2021–2022 and 2023–2024 sampling-frame regimes. The separation between 2022 and 2023 represents a sampling-frame boundary rather than a substantive temporal contrast. Values are formative scores on a 0–1 scale and should not be interpreted as causal year effects.

The environmental and resource-management profile was slightly higher in 2022 than in 2021 and slightly lower in 2024 than in 2023. The secondary overall profile was 0.204 [0.201, 0.207] in 2021 and 0.194 [0.191, 0.198] in 2022, whereas the 2023 and 2024 estimates were nearly identical. When the social access and capacity profile was excluded, the overall estimates for 2021 and 2022 were similar, indicating that the difference in the secondary overall profile was primarily associated with the social access and capacity components.

3.2. Selected Indicators in Original Units

3.2.1. Economic and Productive Indicators

Panel A of Table 5 presents selected economic and productive indicators in their original units. Estimated milk production ranged from 2300.117 kg in 2023 to 3285.457 kg in 2022. The confidence interval for 2022 was comparatively wide, indicating greater uncertainty around the corresponding population estimate. Milk production per cow

showed less annual variation, ranging from 785.739 kg/head in 2023 to 846.865 kg/head in 2022, while the estimated share of milk sold ranged from 0.322 in 2024 to 0.366 in 2022.

Table 5. Selected economic, productive, and environmental/resource-management indicators in original units.

Panel A. Economic and productive indicators					
Indicator	Unit/scale	2021	2022	2023	2024
Milk production	kg	2846.373 [2403.791, 3288.955]	3285.457 [2151.648, 4419.267]	2300.117 [1976.329, 2623.905]	2890.370 [2465.276, 3315.464]
Milk production per cow	kg/head	817.281 [768.115, 866.446]	846.865 [793.771, 899.959]	785.739 [724.592, 846.887]	836.726 [782.673, 890.779]
Share of milk sold	0–1	0.325 [0.291, 0.360]	0.366 [0.328, 0.404]	0.360 [0.311, 0.409]	0.322 [0.288, 0.356]
Panel B. Environmental and resource-management indicators					
Indicator	Unit/scale	2021	2022	2023	2024
Pasture closure	0/1	0.129 [0.113, 0.146]	0.145 [0.125, 0.165]	0.152 [0.118, 0.187]	0.151 [0.128, 0.173]
Pasture reseeding	0/1	0.019 [0.015, 0.024]	0.029 [0.021, 0.036]	0.026 [0.013, 0.040]	0.017 [0.006, 0.028]
Silvopastoral system	0/1	0.011 [0.008, 0.014]	0.010 [0.007, 0.013]	0.022 [0.006, 0.039]	0.021 [0.006, 0.036]

Note: Values are survey-weighted means or proportions. Values in brackets are 95% design-based confidence intervals. Milk-volume indicators were calculated only for observations with valid information for their relevant denominators. Exact definitions, reference periods, denominators, and ENA source variables are reported in Appendix A Tables A1 and A2.

Milk production showed greater annual variation than milk production per cow. The lowest estimated milk production occurred in 2023, followed by a higher estimate in 2024. This pattern should be interpreted cautiously because the ENA rounds are independent annual cross-sections and because milk-volume indicators were calculated only for observations with valid information for the corresponding denominators. Therefore, annual differences may reflect a combination of sample composition, herd structure, reporting conditions, denominator availability, or contextual factors not directly observed in the survey.

These estimates should not be interpreted as changes within the same agricultural producer units or as evidence of causal effects. The available ENA data do not allow the observed variation in milk production to be attributed directly to specific programs, funding levels, technology adoption, feeding strategies, animal-health interventions, climatic conditions, or market changes. Accordingly, milk-production indicators are interpreted as descriptive monitoring signals and should be read together with service-access, training, organizational, and resource-management indicators.

3.2.2. Environmental and Resource-Management Indicators

Panel B of Table 5 and Figure 2 reports selected pasture and resource-management practices. Pasture closure was reported by between 12.9% and 15.2% of the monitored producer population. Pasture reseeding was less common, with estimated proportions ranging from 1.7% to 2.9%. Reported adoption of silvopastoral systems ranged from 1.0% to 2.2%.

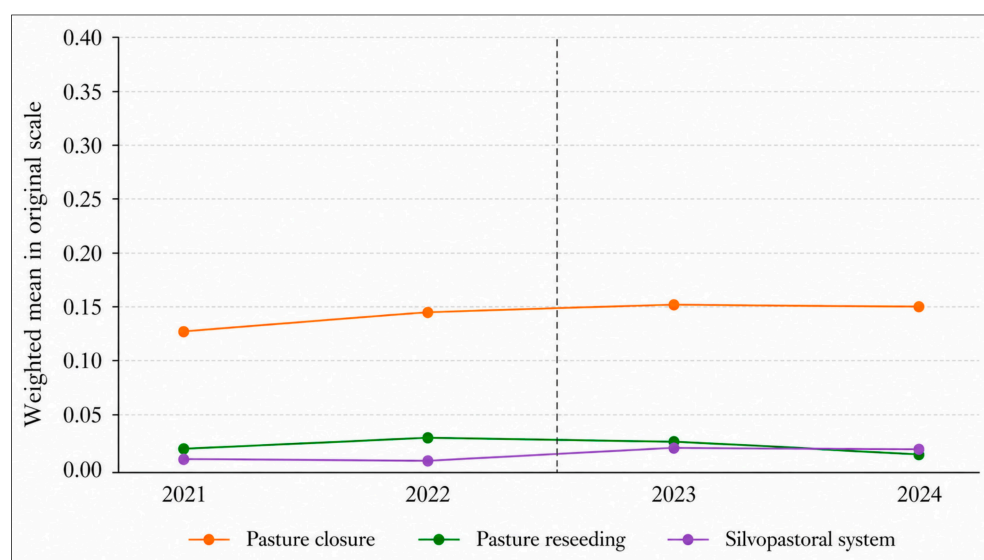


Figure 2. Selected environmental and resource-management indicators in original units. Points and lines represent survey-weighted proportions. The vertical separation marks the 2022–2023 sampling-frame boundary. Annual values describe independent cross-sections and should not be interpreted as causal effects.

The differences in prevalence across these practices show that they represent distinct management components rather than interchangeable manifestations of a single environmental construct. They should therefore be interpreted individually and as components of a formative environmental and resource-management profile, rather than as direct measurements of environmental performance.

3.3. Social Access and Capacity Components

Table 6 decomposes the social access and capacity profile into its component indicators. This decomposition is important because the profile is a formative monitoring summary rather than a validated psychometric scale.

Table 6. Social access and capacity components by year.

Outcome	2021	2022	2023	2024
Livestock training	0.122 [0.113, 0.130]	0.076 [0.069, 0.084]	0.076 [0.063, 0.090]	0.075 [0.052, 0.098]
Technical assistance	0.062 [0.055, 0.068]	0.037 [0.032, 0.042]	0.025 [0.017, 0.033]	0.023 [0.010, 0.037]
Agricultural information use	0.824 [0.814, 0.834]	0.728 [0.716, 0.740]	0.889 [0.873, 0.906]	0.880 [0.851, 0.908]
Producer experience proxy	0.481 [0.475, 0.487]	0.485 [0.479, 0.492]	0.455 [0.442, 0.467]	0.473 [0.453, 0.493]
Organization participation intensity	0.041 [0.036, 0.045]	0.042 [0.038, 0.046]	0.037 [0.030, 0.045]	0.059 [0.043, 0.074]
Social access and capacity profile	0.306 [0.300, 0.311]	0.274 [0.267, 0.280]	0.296 [0.286, 0.306]	0.302 [0.295, 0.309]

Note: Livestock training, technical assistance, and agricultural information use are reported as survey-weighted proportions. Producer experience and organization participation intensity are reported as standardized 0–1 component scores. The social access and capacity profile is the formative mean of its available components. Values in brackets are 95% design-based confidence intervals.

Within the 2021–2022 sampling-frame regime, agricultural information use was lower in 2022, at 0.728 [0.716, 0.740], than in 2021, at 0.824 [0.814, 0.834]. Livestock training was estimated at 0.122 [0.113, 0.130] in 2021 and 0.076 [0.069, 0.084] in 2022. Technical assistance was also lower in 2022, at 0.037 [0.032, 0.042], than in 2021, at 0.062 [0.055, 0.068].

The producer experience proxy and organization participation intensity showed comparatively limited differences between 2021 and 2022. Consequently, the social access and capacity profile was lower in 2022 than in 2021.

Within the 2023–2024 regime, the social access and capacity profile estimates were similar. Agricultural information use remained comparatively high, whereas technical assistance and livestock training remained low. Organization participation intensity was higher in 2024 than in 2023, although the absolute level remained limited.

These indicators describe service access, information use, an accumulated-experience proxy, and organizational participation, as captured by ENA. They should not be interpreted as a complete assessment of social sustainability.

3.4. Within-Regime Regression Contrasts

Table 7 presents adjusted contrasts between annual cross-sections within each sampling-frame regime. The coefficients represent the adjusted difference for the later year minus the earlier year.

Table 7. Survey-weighted adjusted contrasts within-sampling-frame regimes.

Monitoring Profile	Contrast	Adjusted Difference [95% CI]	p-Value	N
Economic and productive profile	2022 vs. 2021	−0.004 [−0.011, 0.002]	0.196	16,066
Economic and productive profile	2024 vs. 2023	0.007 [−0.005, 0.019]	0.234	26,261
Social access and capacity profile	2022 vs. 2021	−0.032 [−0.040, −0.024]	<0.001	16,066
Social access and capacity profile	2024 vs. 2023	0.004 [−0.009, 0.017]	0.525	26,261
Environmental and resource-management profile	2022 vs. 2021	0.006 [0.000, 0.011]	0.038	16,066
Environmental and resource-management profile	2024 vs. 2023	−0.003 [−0.012, 0.006]	0.494	26,261
Overall formative profile (secondary)	2022 vs. 2021	−0.010 [−0.015, −0.006]	<0.001	16,066
Overall formative profile (secondary)	2024 vs. 2023	0.003 [−0.004, 0.010]	0.458	26,261
Overall profile excluding social access and capacity (sensitivity)	2022 vs. 2021	0.001 [−0.004, 0.005]	0.779	16,066
Overall profile excluding social access and capacity (sensitivity)	2024 vs. 2023	0.002 [−0.006, 0.010]	0.599	26,261

Note: Coefficients represent the adjusted difference for the later year minus the earlier year within each sampling-frame regime. Models were adjusted for herd stock, land area, producer education, and region. Values in brackets are 95% design-based confidence intervals. Analytical N includes observations with complete information for the outcome and adjustment variables. The 2023–2024 analytical N is four observations lower than the corresponding descriptive sample because of missing information in at least one adjustment variable. Coefficients and confidence limits are rounded to three decimals; therefore, a confidence limit displayed as 0.000 may be slightly greater than zero in the unrounded statistical output. Estimates are descriptive and should not be interpreted causally.

Within the 2021–2022 regime, the social access and capacity profile was lower in 2022 than in 2021, with an adjusted difference of -0.032 [$-0.040, -0.024$] ($p < 0.001$). The economic and productive profile was not statistically distinguishable between the two years. The environmental and resource-management profile showed a small positive adjusted difference of 0.006 [$0.000, 0.011$] ($p = 0.038$).

The secondary overall profile was lower in 2022 than in 2021, with an adjusted difference of -0.010 [$-0.015, -0.006$] ($p < 0.001$). However, when the social access and capacity profile was excluded, the adjusted difference was close to zero and was not statistically distinguishable from zero (coefficient = 0.001 , $p = 0.779$). This indicates that the adjusted difference in the secondary overall profile was primarily associated with the social access and capacity components.

Within the 2023–2024 sampling-frame regime, none of the economic and productive, social access and capacity, environmental and resource-management, or secondary overall profile contrasts was statistically distinguishable from zero.

These coefficients represent adjusted descriptive differences between independent annual cross-sections. They should not be interpreted as causal year effects or as changes within the same agricultural producer units.

3.5. Sensitivity Analyses

The sensitivity analyses did not change the principal interpretation of the results. Applying minimum indicator-availability thresholds of 50% and 70%, excluding derivative output, excluding producer age, and using sampling-regime-specific scaling changed the absolute levels of some formative profiles but did not reverse the direction of the principal within-regime findings.

For example, the secondary overall profile for 2022 was 0.194 [$0.191, 0.198$] under the primary specification and 0.177 [$0.173, 0.181$] when producer age was excluded. Despite this change in the absolute profile value, the lower social access and capacity profile in 2022 remained evident.

Excluding the social access and capacity profile eliminated the adjusted difference in the secondary overall profile between 2021 and 2022. The overall profile excluding social access and capacity was estimated at 0.153 [$0.150, 0.157$] in 2021 and 0.155 [$0.151, 0.158$] in 2022, and the corresponding adjusted contrast was not statistically distinguishable from zero.

Regime-specific 1st–99th percentile scaling produced only limited differences in mean profile estimates compared with pooled scaling. Complete-case scoring across all 27 formative indicators was not feasible because no survey year contained complete information for every indicator, primarily because of structural missingness in optional and derived milk-production and allocation variables.

Complete sensitivity estimates are reported in Appendix A Table A5, and the comparison between pooled and sampling-regime-specific scaling is presented in Appendix A Figure A1. Collectively, these analyses indicate that the most consistent within-regime difference concerned social access and capacity between 2021 and 2022, whereas the main profiles in the 2023–2024 regime showed no statistically detectable adjusted differences.

4. Discussion

4.1. Main Findings and Contribution of the National-Scale Approach

This study shows that ENA microdata can support national monitoring of sustainability-relevant conditions among Peruvian dairy cattle producers when the analytical population, indicator construction, missingness, survey design, and sampling-frame discontinuities are handled explicitly. The resulting profiles should be interpreted as proxy-based formative

monitoring summaries, not as causal trends, complete farm sustainability assessments, or longitudinal changes within the same producer units.

The separation between the 2021–2022 and 2023–2024 sampling-frame regimes is central to this interpretation. Treating the four ENA rounds as a single continuous trend would risk attributing survey-frame differences to substantive sustainability change. By restricting adjusted contrasts to comparisons within the same regime, the analysis provides a more defensible basis for monitoring annual differences while preserving the survey's national representativeness.

The strongest within-regime result was a lower social access and capacity profile in 2022 than in 2021. This difference was mainly associated with lower observed levels of agricultural information use, livestock training, and technical assistance. This should not be interpreted as a validated decline in social sustainability because ENA does not directly measure labor conditions, access to health services, household vulnerability, or broader human capital. Rather, it indicates a reduction in the specific access and capacity conditions that the survey captured.

Even with this limitation, the signal is agriculturally meaningful. Access to technical assistance, training, information, and producer organizations can influence producers' ability to improve feeding, animal health, pasture management, milk quality, and market participation. The disappearance of the adjusted difference in the secondary overall profile when the social access and capacity profile was excluded further indicates that the apparent 2021–2022 reduction in the overall profile was mainly driven by the observed social access and capacity components.

Within the 2023–2024 sampling-frame regime, none of the main adjusted profiles showed statistically significant differences. This finding indicates short-term stability in the monitored indicators, but it does not imply that dairy systems were structurally sustainable or that relevant changes did not occur. Stability may reflect true year-to-year similarity, limited sensitivity of the available ENA variables, or both. Therefore, the low absolute levels of several management indicators remain more important for interpretation than the absence of short-run adjusted differences.

This national-scale contribution complements farm-level and regional sustainability studies in Peru and Latin America. Local assessments can provide deeper biophysical, agroecological, economic, and participatory information, but they usually do not offer recurrent nationally representative estimates [19–21]. In contrast, the ENA-based approach sacrifices local detail in exchange for national coverage, repeated measurement, explicit survey weighting, and the ability to monitor comparable domains over time. This difference in scale is the study's main methodological contribution.

4.2. Agricultural Systems and Management Implications

The indicator-level results point to concrete domains for dairy-sector monitoring and policy action. In 2024, technical assistance reached only 0.023 [0.014, 0.033], livestock training reached 0.075 [0.061, 0.090], pasture reseeding reached 0.017 [0.006, 0.028], and reported use of silvopastoral systems reached 0.021 [0.006, 0.036]. Although these values depend on ENA definitions and coverage, their low levels suggest that extension services, specialized training, pasture renewal, and tree–pasture integration remain weakly diffused among the monitored producer population [31,32].

These findings indicate that dairy-sector development should not be evaluated solely by production indicators. Productive capacity can be constrained by limited access to advice, inadequate training coverage, low organizational participation, and limited adoption of resource-management practices. Policy efforts aimed at increasing milk production

should therefore be accompanied by sustained investment in technical assistance, livestock training, animal-health support, pasture management, and producer organizations [33].

The low prevalence of pasture reseeding and silvopastoral systems is relevant to environmental and resource-management planning. These practices may contribute to forage availability, soil cover, microclimate regulation, and more diversified land management. However, ENA does not directly measure soil quality, nutrient balances, carbon storage, water-use efficiency, biodiversity, or greenhouse gas emissions. Therefore, the results should be interpreted as evidence of limited adoption of selected management practices, not as direct evidence of environmental performance.

The findings also suggest a cautious entry point for circular-economy monitoring in dairy systems. Circularity in livestock production should not be framed only around downstream waste valorization or processing. It also depends on farm-level practices such as pasture renewal, forage conservation, manure management, crop–livestock integration, and tree–pasture systems. The current ENA variables do not measure material flows, manure destinations, nutrient recycling, or energy use, but they identify domains where future survey modules could improve monitoring of circular resource use.

For policy monitoring, ENA should preserve stable indicator definitions, document changes in sampling frames and questionnaire routing, and publish coverage and missingness diagnostics together with headline estimates. Future modules could strengthen measurement of manure management, rotational grazing, forage conservation, soil cover practices, crop–livestock residue use, milk quality, animal health and welfare, water and energy use, farm costs and revenues, and producer labor conditions. These additions would help move from proxy-based monitoring toward more complete sustainability and circular-economy assessment.

The observed variation in milk production cannot be attributed directly to specific programs, funding levels, technology adoption, feeding strategies, animal-health interventions, or climatic conditions because these mechanisms are not measured with sufficient detail in the current ENA analytical structure. This limitation is important for sustainability monitoring. Higher dairy production is not necessarily more sustainable unless it is achieved while maintaining or improving the natural resource base. Future ENA modules could therefore include more detailed information on feeding systems, forage availability, breed composition, animal health, veterinary access, reproductive management, program participation, technology adoption, input use, climate shocks, milk quality, farm-gate prices, production costs, and manure or residue management. These additions would allow future analyses to explain whether changes in milk production are associated with improved productive efficiency, better advisory support, or greater pressure on natural resources.

4.3. Measurement Implications

The profiles developed in this study were specified as formative because their components represent distinct and complementary characteristics of dairy systems. Technical assistance, training, agricultural information use, producer organization, milk commercialization, productive capacity, and pasture management are not interchangeable expressions of a single latent construct. Each indicator describes a different condition that may contribute to the broader monitoring profile.

For this reason, internal-consistency statistics should not be used as the primary criterion for validating the profiles. Low correlations or low alpha values do not prove that a profile is formative, but they are consistent with the conceptual expectation that the indicators capture complementary dimensions. The validity of the profiles depends instead on conceptual relevance, transparent construction, indicator traceability, sufficient coverage, clear directionality, sensitivity analysis, and interpretability.

This choice of measurement limits the claims that can be made. The study does not measure a single latent construct called “sustainability.” It constructs three monitoring profiles: economic and productive conditions, social access and capacity, and environmental and resource management. The secondary overall profile is useful as a summary, but it is compensatory and may conceal differences among domains. Therefore, interpretation should prioritize domain-level and indicator-level results over the overall score.

The sensitivity analyses support this interpretation. Excluding producer age reduced dependence on a conceptually ambiguous experience proxy. Excluding derivative output addressed missingness in production-allocation variables. Minimum-availability thresholds and regime-specific scaling were used to test whether the results depended on partial observations or on the main scaling reference. Across these checks, the main interpretation remained stable: the biggest within-regime difference concerned social access and capacity between 2021 and 2022, while the 2023–2024 profiles remained comparatively stable.

4.4. Limitations

The findings should be interpreted within the scope of the ENA data. The survey was not designed as a comprehensive sustainability assessment; therefore, the profiles constructed in this study should be read as sustainability-relevant proxies rather than complete measures of economic viability, social well-being, environmental integrity, governance, resilience, or circularity. Important domains such as greenhouse gas emissions, input intensity, manure management, nutrient balances, soil conditions, water conservation, biodiversity, animal welfare, profitability, milk quality, labor conditions, access to health services, and broader human capital were either absent or only partially observed.

Temporal interpretation is also limited by repeated cross-sectional design and the 2023 sampling-frame transition. ENA does not follow the same producer units over time, so annual estimates describe independent samples rather than within-farm changes. The separation of the 2021–2022 and 2023–2024 sampling-frame regimes reduces the risk of overinterpreting frame-related differences, but it does not create a continuous four-year trend. The 2021–2024 window is also too short to identify long-term structural trajectories or persistent sustainability transitions.

Additional caution is required because several milk-production, milk-allocation, and derivative-output variables presented missingness or structural non-applicability, and because equal-weight aggregation assumes compensation among indicators in the absence of nationally validated stakeholder-derived weights. Some indicators, including production volume, milk production per hectare, forest area, natural pasture area, household milk allocation, and producer age, may reflect resource endowments, farm size, market access, demographic structure, or production objectives rather than management quality alone. These limitations do not invalidate the monitoring protocol, but they define its appropriate use: a national baseline, a transparent synthesis of ENA-available information, and an agenda for improving future agricultural survey modules rather than a replacement for detailed farm assessments, participatory MESMIS applications, LCA, SAFA, IDEA, or other comprehensive sustainability frameworks.

5. Conclusions

National agricultural survey data can support monitoring of sustainability-relevant profiles in Peruvian dairy cattle systems when the analytical population, missingness, indicator direction, aggregation rules, and sampling-frame regimes are explicitly accounted for. This study provides a frame-aware, MESMIS-informed monitoring protocol using ENA 2021–2024 microdata and shows that repeated official surveys can generate a reproducible national baseline when their limits are treated as part of the evidence rather than ignored.

The empirical results indicate that the most relevant within-regime signal was located in the social access and capacity profile. The lower 2022 profile relative to 2021 was mainly associated with lower observed levels of agricultural information use, livestock training, and technical assistance. Within the 2023–2024 sampling-frame regime, the main adjusted profiles remained comparatively stable. These findings should not be interpreted as causal trends or as changes within the same farms, but as survey-weighted monitoring evidence from independent annual cross-sections.

The indicator-level results also point to concrete constraints for dairy-sector monitoring and policy design. Low coverage of technical assistance and livestock training suggests limited diffusion of advisory and capacity-building services, while low adoption of pasture reseeding and silvopastoral systems indicates that selected resource-management practices remain weakly extended among the monitored producer population. These patterns are relevant for productivity, resilience, and future circular-resource monitoring, although ENA does not directly measure environmental performance, nutrient flows, greenhouse gas emissions, or farm-level circularity.

For policy and survey design, the study offers three practical implications. First, ENA-based dairy monitoring should report sampling-frame regimes and avoid interpreting cross-frame differences as substantive year-to-year change. Second, sustainability reporting should combine formative profiles with raw indicators, as aggregate scores can mask specific management and service-access gaps. Third, future ENA modules should strengthen variables related to manure management, soil cover conditions, rotational grazing, forage conservation, crop–livestock residue use, water and energy use, milk quality, animal welfare, farm costs, and producer labor conditions.

The study, therefore, contributes a cautious but usable national monitoring baseline for Peruvian dairy systems. Its value lies in transparently organizing the available ENA information, identifying policy-relevant gaps, and defining the conditions under which recurrent agricultural surveys can inform sustainability monitoring. The proposed profiles should not be used as definitive sustainability rankings of farms, but as a reproducible tool for national monitoring, prioritization, and future survey improvement.

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Data Availability Statement: The original data presented in the study are openly available in Peru's official statistical data systems and the Plataforma Nacional de Datos Abiertos at <https://proyectos.inei.gob.pe/microdatos/> and <https://www.datosabiertos.gob.pe/> (both accessed

on 3 June 2026). The harmonized processing scripts and derived tables generated for this study are organized in the project repository and will be made available upon publication.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

This section embeds the appendix tables and visual support files generated by the reproducible pipeline for reviewer inspection.

Table A1. Eligibility traceability for the ENA dairy cattle analytical sample.

Criterion	Reader-Facing Criterion	Interpretation	Years	Retained N	Notes
Agricultural producer unit in ENA frame	ENA producer frame	Agricultural producer units covered by the annual ENA survey frame.	2021–2024	42,331	Full annual frame counts are reported in the sample-flow outputs.
Complete interview and valid agricultural producer record	Complete interview and valid producer record	Producer record classified as valid and complete interview.	2021–2024	42,331	Applied before livestock and dairy cattle filtering in the reproducible Stata pipeline.
Livestock activity	Reported livestock activity	Producer reports livestock activity in harmonized ENA modules.	2021–2024	42,331	Intermediate counts are retained in sample-flow tables.
Dairy cattle activity/cows in milk	Reported dairy cattle activity/cows in milk greater than zero	Harmonized dairy cattle eligibility variable used as the producer-level inclusion rule for dairy cattle activity/cows in milk.	2021–2024	42,331	This eligibility rule does not require complete milk-volume allocation records; missingness is reported separately.

Table A2. Indicator missingness by year.

Indicator	Reader-Facing Indicator	Year	N	Non-Missing	Missing	Missing Percent
Total milk production	Total milk production	2021	8247	4863	3384	41.03
Total milk production	Total milk production	2022	7819	4442	3377	43.19
Total milk production	Total milk production	2023	11,789	6888	4901	41.57
Total milk production	Total milk production	2024	14,476	8540	5936	41.01
Milk sold	Milk sold	2021	8247	4863	3384	41.03
Milk sold	Milk sold	2022	7819	4442	3377	43.19
Milk sold	Milk sold	2023	11,789	6888	4901	41.57
Milk sold	Milk sold	2024	14,476	8540	5936	41.01
Share of milk sold	Share of milk sold	2021	8247	4863	3384	41.03
Share of milk sold	Share of milk sold	2022	7819	4442	3377	43.19
Share of milk sold	Share of milk sold	2023	11,789	6888	4901	41.57
Share of milk sold	Share of milk sold	2024	14,476	8540	5936	41.01
Milk for household consumption	Milk for household consumption	2021	8247	4863	3384	41.03
Milk for household consumption	Milk for household consumption	2022	7819	4442	3377	43.19
Milk for household consumption	Milk for household consumption	2023	11,789	6888	4901	41.57
Milk for household consumption	Milk for household consumption	2024	14,476	8540	5936	41.01
Share for self-consumption	Share for self-consumption	2021	8247	4863	3384	41.03
Share for self-consumption	Share for self-consumption	2022	7819	4442	3377	43.19
Share for self-consumption	Share for self-consumption	2023	11,789	6888	4901	41.57
Share for self-consumption	Share for self-consumption	2024	14,476	8540	5936	41.01
Milk for derivatives	Milk for derivatives	2021	8247	4863	3384	41.03

Table A2. Cont.

Indicator	Reader-Facing Indicator	Year	N	Non-Missing	Missing	Missing Percent
Milk for derivatives	Milk for derivatives	2022	7819	4442	3377	43.19
Milk for derivatives	Milk for derivatives	2023	11,789	6888	4901	41.57
Milk for derivatives	Milk for derivatives	2024	14,476	8540	5936	41.01
Share processed into derivatives	Share processed into derivatives	2021	8247	4863	3384	41.03
Share processed into derivatives	Share processed into derivatives	2022	7819	4442	3377	43.19
Share processed into derivatives	Share processed into derivatives	2023	11,789	6888	4901	41.57
Share processed into derivatives	Share processed into derivatives	2024	14,476	8540	5936	41.01
Cows in milk	Cows in milk	2021	8247	4863	3384	41.03
Cows in milk	Cows in milk	2022	7819	4442	3377	43.19
Cows in milk	Cows in milk	2023	11,789	6888	4901	41.57
Cows in milk	Cows in milk	2024	14,476	8540	5936	41.01
Milk per cow	Milk per cow	2021	8247	4863	3384	41.03
Milk per cow	Milk per cow	2022	7819	4442	3377	43.19
Milk per cow	Milk per cow	2023	11,789	6888	4901	41.57
Milk per cow	Milk per cow	2024	14,476	8540	5936	41.01
Low bovine mortality	Bovine mortality	2021	8247	8247	0	0.0
Low bovine mortality	Bovine mortality	2022	7819	7819	0	0.0
Low bovine mortality	Bovine mortality	2023	11,789	11,789	0	0.0
Low bovine mortality	Bovine mortality	2024	14,476	14,476	0	0.0
Herd replacement	Herd replacement	2021	8247	7917	330	4.0
Herd replacement	Herd replacement	2022	7819	7462	357	4.57
Herd replacement	Herd replacement	2023	11,789	11,482	307	2.6
Herd replacement	Herd replacement	2024	14,476	14,105	371	2.56
Milk-use diversification	Milk-use diversification	2021	8247	4863	3384	41.03
Milk-use diversification	Milk-use diversification	2022	7819	4442	3377	43.19
Milk-use diversification	Milk-use diversification	2023	11,789	6888	4901	41.57
Milk-use diversification	Milk-use diversification	2024	14,476	8540	5936	41.01
Certified semen or embryos	Certified semen use	2021	8247	8247	0	0.0
Certified semen or embryos	Certified semen use	2022	7819	7819	0	0.0
Certified semen or embryos	Certified semen use	2023	11,789	11,789	0	0.0
Certified semen or embryos	Certified semen use	2024	14,476	14,476	0	0.0
Derivative output	Derivative-output quantity	2021	8247	3040	5207	63.14
Derivative output	Derivative-output quantity	2022	7819	2454	5365	68.61
Derivative output	Derivative-output quantity	2023	11,789	4343	7446	63.16
Derivative output	Derivative-output quantity	2024	14,476	5577	8899	61.47
Livestock training	Livestock training	2021	8247	8247	0	0.0
Livestock training	Livestock training	2022	7819	7819	0	0.0
Livestock training	Livestock training	2023	11,789	11,789	0	0.0
Livestock training	Livestock training	2024	14,476	14,476	0	0.0
Technical assistance	Technical assistance	2021	8247	8247	0	0.0
Technical assistance	Technical assistance	2022	7819	7819	0	0.0
Technical assistance	Technical assistance	2023	11,789	11,789	0	0.0
Technical assistance	Technical assistance	2024	14,476	14,476	0	0.0
Agricultural information use	Agricultural information use	2021	8247	8247	0	0.0
Agricultural information use	Agricultural information use	2022	7819	7819	0	0.0
Agricultural information use	Agricultural information use	2023	11,789	11,789	0	0.0
Agricultural information use	Agricultural information use	2024	14,476	14,476	0	0.0
Producer experience proxy	Producer experience proxy	2021	8247	8247	0	0.0
Producer experience proxy	Producer experience proxy	2022	7819	7819	0	0.0
Producer experience proxy	Producer experience proxy	2023	11,789	11,789	0	0.0
Producer experience proxy	Producer experience proxy	2024	14,476	14,476	0	0.0
Organization participation intensity	Organization participation intensity	2021	8247	8247	0	0.0

Table A2. Cont.

Indicator	Reader-Facing Indicator	Year	N	Non-Missing	Missing	Missing Percent
Organization participation intensity	Organization participation intensity	2022	7819	7819	0	0.0
Organization participation intensity	Organization participation intensity	2023	11,789	11,789	0	0.0
Organization participation intensity	Organization participation intensity	2024	14,476	14,476	0	0.0
Milk per hectare	Milk per hectare	2021	8247	4847	3400	41.23
Milk per hectare	Milk per hectare	2022	7819	4412	3407	43.57
Milk per hectare	Milk per hectare	2023	11,789	6882	4907	41.62
Milk per hectare	Milk per hectare	2024	14,476	8534	5942	41.05
Managed natural pasture area	Managed pasture area	2021	8247	8213	34	0.41
Managed natural pasture area	Managed pasture area	2022	7819	7770	49	0.63
Managed natural pasture area	Managed pasture area	2023	11,789	11,779	10	0.08
Managed natural pasture area	Managed pasture area	2024	14,476	14,467	9	0.06
Pasture closure	Pasture closure	2021	8247	8247	0	0.0
Pasture closure	Pasture closure	2022	7819	7819	0	0.0
Pasture closure	Pasture closure	2023	11,789	11,789	0	0.0
Pasture closure	Pasture closure	2024	14,476	14,476	0	0.0
Pasture reseeding	Pasture reseeding	2021	8247	8247	0	0.0
Pasture reseeding	Pasture reseeding	2022	7819	7819	0	0.0
Pasture reseeding	Pasture reseeding	2023	11,789	11,789	0	0.0
Pasture reseeding	Pasture reseeding	2024	14,476	14,476	0	0.0
Forage within natural pasture	Natural-pasture forage use	2021	8247	8247	0	0.0
Forage within natural pasture	Natural-pasture forage use	2022	7819	7819	0	0.0
Forage within natural pasture	Natural-pasture forage use	2023	11,789	11,789	0	0.0
Forage within natural pasture	Natural-pasture forage use	2024	14,476	14,476	0	0.0
Silvopastoral system	Silvopastoral system	2021	8247	8247	0	0.0
Silvopastoral system	Silvopastoral system	2022	7819	7819	0	0.0
Silvopastoral system	Silvopastoral system	2023	11,789	11,789	0	0.0
Silvopastoral system	Silvopastoral system	2024	14,476	14,476	0	0.0
Low unmanaged natural pasture area	Unmanaged pasture area	2021	8247	8213	34	0.41
Low unmanaged natural pasture area	Unmanaged pasture area	2022	7819	7770	49	0.63
Low unmanaged natural pasture area	Unmanaged pasture area	2023	11,789	11,779	10	0.08
Low unmanaged natural pasture area	Unmanaged pasture area	2024	14,476	14,467	9	0.06
Forest area	Forest area	2021	8247	8213	34	0.41
Forest area	Forest area	2022	7819	7770	49	0.63
Forest area	Forest area	2023	11,789	11,779	10	0.08
Forest area	Forest area	2024	14,476	14,467	9	0.06

Table A3. Regime-specific scaling sensitivity.

Outcome	Year	Frame Regime	Mean Pooled	Mean Regime-Specific	Mean Difference
Economic formative profile	2021	2021–2022	0.1439676048692152	0.1427660978096264	−0.0012015070595887
Economic formative profile	2022	2021–2022	0.1414718991275175	0.1414149224321889	−5.6976695328642135
Economic formative profile	2023	2023–2024	0.1341588240969885	0.1366412320037457	0.0024824079067571
Economic formative profile	2024	2023–2024	0.1356989599246569	0.1379469955409669	0.0022480356163099
Social access and capacity profile	2021	2021–2022	0.3056779230033801	0.3021124862737859	−0.0035654367295941
Social access and capacity profile	2022	2021–2022	0.2737503646905529	0.2701925527765673	−0.0035578119139855
Social access and capacity profile	2023	2023–2024	0.2964546843900296	0.2982041100232119	0.0017494256331822
Social access and capacity profile	2024	2023–2024	0.3019574373935344	0.3036848685311341	0.0017274311375997
Environmental formative profile	2021	2021–2022	0.16261390129858	0.1611542981726486	−0.0014596031259314
Environmental formative profile	2022	2021–2022	0.1680831358180752	0.1657992966944488	−0.0022838391236263
Environmental formative profile	2023	2023–2024	0.1698787566700844	0.170312319209657	0.0004335625395726
Environmental formative profile	2024	2023–2024	0.1639074647615176	0.1637800684276081	−0.0001273963339095
Overall formative profile (secondary)	2021	2021–2022	0.2040864763903918	0.2020109607520203	−0.0020755156383714
Overall formative profile (secondary)	2022	2021–2022	0.1944351332120486	0.192468923967735	−0.0019662092443136
Overall formative profile (secondary)	2023	2023–2024	0.2001640883857008	0.2017192204122049	0.001555132026504
Overall formative profile (secondary)	2024	2023–2024	0.200521287359903	0.201803977499903	0.00128269014
Overall profile excluding social (sensitivity)	2021	2021–2022	0.1532907530838976	0.1519601979911375	−0.0013305550927601
Overall profile excluding social (sensitivity)	2022	2021–2022	0.1547775174727964	0.1536071095633189	−0.0011704079094775
Overall profile excluding social (sensitivity)	2023	2023–2024	0.1520187903835364	0.1534767756067014	0.0014579852231649
Overall profile excluding social (sensitivity)	2024	2023–2024	0.1498032123430872	0.1508635319842875	0.0010603196412002

Table A4. Milk-volume missingness and indicator availability.

Year	Frame Regime	N	Milk-Volume Non-Missing N	Milk-Volume Non-Missing Percent	Median Economic Indicators Available	Median Social Indicators Available	Median Environmental Indicators Available
2021	2021–2022	8247	4863	58.97	12.0	5.0	8.0
2022	2021–2022	7819	4442	56.81	12.0	5.0	8.0
2023	2023–2024	11,789	6888	58.43	12.0	5.0	8.0
2024	2023–2024	14,476	8540	58.99	12.0	5.0	8.0

Table A5. Survey design threshold, no-derivative, and no-age sensitivity.

Sensitivity Outcome	Year	Frame Regime	Estimate	N
Main overall formative profile	2021	2021–2022	0.204 [0.201, 0.207]	8247
Main overall formative profile	2022	2021–2022	0.194 [0.191, 0.198]	7819
Main overall formative profile	2023	2023–2024	0.200 [0.194, 0.206]	11,789
Main overall formative profile	2024	2023–2024	0.201 [0.197, 0.204]	14,476
Overall profile, >=50% indicators per dimension	2021	2021–2022	0.224 [0.221, 0.227]	8247
Overall profile, >=50% indicators per dimension	2022	2021–2022	0.213 [0.210, 0.217]	7819
Overall profile, >=50% indicators per dimension	2023	2023–2024	0.224 [0.218, 0.229]	11,789
Overall profile, >=50% indicators per dimension	2024	2023–2024	0.225 [0.221, 0.229]	14,476
Overall profile, >=70% indicators per dimension	2021	2021–2022	0.224 [0.221, 0.227]	8247
Overall profile, >=70% indicators per dimension	2022	2021–2022	0.214 [0.210, 0.217]	7819
Overall profile, >=70% indicators per dimension	2023	2023–2024	0.224 [0.218, 0.229]	11,789
Overall profile, >=70% indicators per dimension	2024	2023–2024	0.225 [0.221, 0.229]	14,476
Overall profile excluding derivative output	2021	2021–2022	0.206 [0.203, 0.209]	8247
Overall profile excluding derivative output	2022	2021–2022	0.196 [0.192, 0.199]	7819
Overall profile excluding derivative output	2023	2023–2024	0.201 [0.195, 0.207]	11,789
Overall profile excluding derivative output	2024	2023–2024	0.202 [0.198, 0.206]	14,476
Economic profile excluding derivative output	2021	2021–2022	0.150 [0.145, 0.155]	8247
Economic profile excluding derivative output	2022	2021–2022	0.145 [0.139, 0.150]	7819
Economic profile excluding derivative output	2023	2023–2024	0.138 [0.127, 0.148]	11,789
Economic profile excluding derivative output	2024	2023–2024	0.140 [0.133, 0.147]	14,476
Overall profile excluding producer age	2021	2021–2022	0.189 [0.186, 0.193]	8247
Overall profile excluding producer age	2022	2021–2022	0.177 [0.173, 0.181]	7819
Overall profile excluding producer age	2023	2023–2024	0.187 [0.181, 0.193]	11,789
Overall profile excluding producer age	2024	2023–2024	0.186 [0.182, 0.190]	14,476
Overall profile excluding social profile	2021	2021–2022	0.153 [0.150, 0.157]	8247
Overall profile excluding social profile	2022	2021–2022	0.155 [0.151, 0.158]	7819
Overall profile excluding social profile	2023	2023–2024	0.152 [0.146, 0.158]	11,789
Overall profile excluding social profile	2024	2023–2024	0.150 [0.145, 0.154]	14,476

Table A6. Complete-case feasibility.

Year	Frame Regime	Complete-Case N Across all Formative Indicators	Interpretation
2021	2021–2022	0	Full complete-case scoring is not feasible because some optional/derived indicators have extensive structural missingness.
2022	2021–2022	0	Full complete-case scoring is not feasible because some optional/derived indicators have extensive structural missingness.
2023	2023–2024	0	Full complete-case scoring is not feasible because some optional/derived indicators have extensive structural missingness.
2024	2023–2024	0	Full complete-case scoring is not feasible because some optional/derived indicators have extensive structural missingness.

Table A7. Design and coverage diagnostics by year.

Year	Sampling-Frame Regime	Unweighted N	Weighted Total	PSUs	Strata Variable	Strata Count	Regions/Departments	Milk-Volume Non-Missing N	Milk-Volume Non-Missing Weighted Percent
2021	2021–2022	8247	810,914.15	1616	dominio	7	24	4863	59.78
2022	2021–2022	7819	731,597.32	1554	dominio	7	24	4442	58.95
2023	2023–2024	11,789	715,335.87	4710	estrato	3493	24	6888	56.81
2024	2023–2024	14,476	826,466.04	5839	estrato	3456	25	8540	56.49

Table A8. Indicator-direction justification.

Indicator	Reader-Facing Indicator	Favorable Direction	Justification/Caveat
Total milk production	Total milk production	Higher	Interpreted as productive capacity and scale; not sufficient evidence of sustainability on its own.
Milk sold	Milk sold	Higher	Interpreted as market participation; household consumption and processing are reported separately.
Share of milk sold	Share of milk sold	Higher	Direction follows the intended monitoring interpretation in the MESMIS-informed profile.
Milk for household consumption	Milk for household consumption	Higher	Interpreted as household food-use capacity/equity proxy; direction is debatable and should be read cautiously.
Share for self-consumption	Share for self-consumption	Higher	Interpreted as household food-use capacity/equity proxy; high values may also indicate weak market integration.
Milk for derivatives	Milk for derivatives	Higher	Direction follows the intended monitoring interpretation in the MESMIS-informed profile.
Share processed into derivatives	Share processed into derivatives	Higher	Direction follows the intended monitoring interpretation in the MESMIS-informed profile.
Cows in milk	Cows in milk	Higher	Direction follows the intended monitoring interpretation in the MESMIS-informed profile.
Milk per cow	Milk per cow	Higher	Direction follows the intended monitoring interpretation in the MESMIS-informed profile.
Low bovine mortality	Bovine mortality	Lower	Direction follows the intended monitoring interpretation in the MESMIS-informed profile.
Herd replacement	Herd replacement	Higher	Interpreted as herd renewal/reliability proxy; exact meaning depends on ENA harmonization.
Milk-use diversification	Milk-use diversification	Higher	Direction follows the intended monitoring interpretation in the MESMIS-informed profile.

Table A8. Cont.

Indicator	Reader-Facing Indicator	Favorable Direction	Justification/Caveat
Certified semen or embryos	Certified semen use	Higher	Direction follows the intended monitoring interpretation in the MESMIS-informed profile.
Derivative output	Derivative-output quantity	Higher	Direction follows the intended monitoring interpretation in the MESMIS-informed profile.
Livestock training	Livestock training	Higher	Direction follows the intended monitoring interpretation in the MESMIS-informed profile.
Technical assistance	Technical assistance	Higher	Direction follows the intended monitoring interpretation in the MESMIS-informed profile.
Agricultural information use	Agricultural information use	Higher	Direction follows the intended monitoring interpretation in the MESMIS-informed profile.
Producer experience proxy	Producer experience proxy	Higher	Producer age is an experience proxy; a no-age sensitivity is reported.
Organization participation intensity	Organization participation intensity	Higher	Direction follows the intended monitoring interpretation in the MESMIS-informed profile.
Milk per hectare	Milk per hectare	Higher	Direction follows the intended monitoring interpretation in the MESMIS-informed profile.
Managed natural pasture area	Managed pasture area	Higher	Area-based pasture indicator; reflects availability / management but not pasture condition.
Pasture closure	Pasture closure	Higher	Direction follows the intended monitoring interpretation in the MESMIS-informed profile.
Pasture reseeding	Pasture reseeding	Higher	Direction follows the intended monitoring interpretation in the MESMIS-informed profile.
Forage within natural pasture	Natural-pasture forage use	Higher	Direction follows the intended monitoring interpretation in the MESMIS-informed profile.
Silvopastoral system	Silvopastoral system	Higher	Direction follows the intended monitoring interpretation in the MESMIS-informed profile.
Low unmanaged natural pasture area	Unmanaged pasture area	Lower	Reverse-scored because unmanaged pasture area is treated as less favorable management.
Forest area	Forest area	Higher	Forest area is a resource-endowment/conservation proxy; it is not direct evidence of forest management quality.

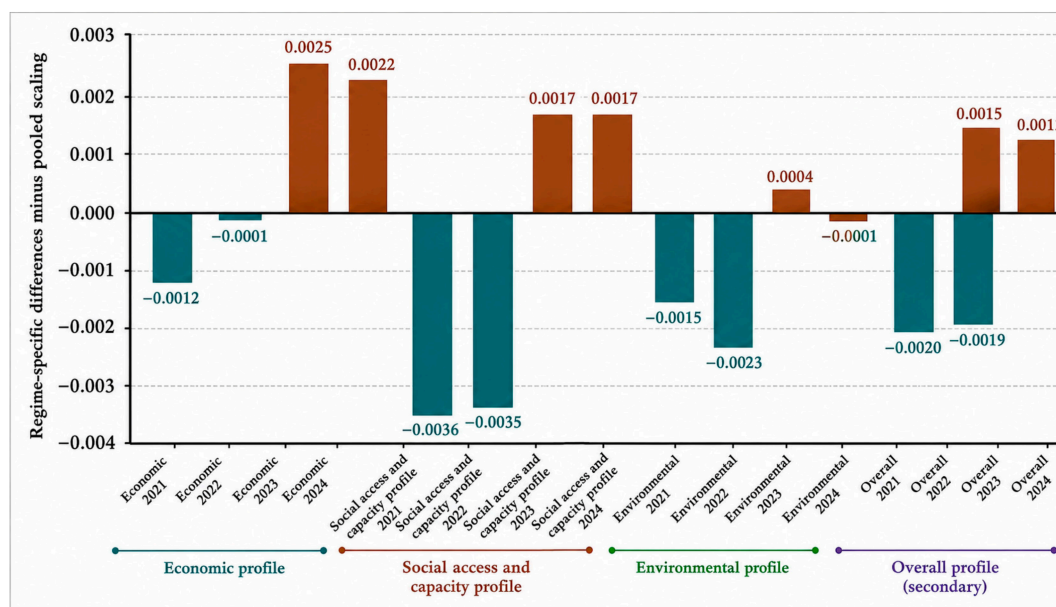


Figure A1. Regime-specific p1–p99 scaling sensitivity.

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