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Environmental Code Reform, Enterprise Abatement Outlays, and Stationary Industrial Emissions: Subnational Evidence from Kazakhstan, 2010–2025

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Abstract

Staggered industrial environmental codes pair multi-year preparatory monitoring windows with scheduled transitions toward best-available-technique permitting and progressive fee multipliers, raising an open mechanism question: do historically emission-intensive industrial regions adjust during early preparatory compliance through enterprise current abatement outlays and end-of-pipe pollutant capture, or does emission-intensity compression emerge as integrated-permit and fee-escalation thresholds arrive? Assembling a boundary-harmonized panel across all 16 consolidated parent regions of Kazakhstan from 2010 to 2025 (N = 256) around Environmental Code No. 400-VI (enacted January 2021, entering into general force July 2021, with Category I integrated permitting and scheduled fee multipliers commencing January 2025), we estimate exposure-gradient regressions with 9,999 null-imposed wild cluster bootstrap replications. Across 2022–2025, one standard deviation higher predetermined 2017–2019 stationary emission exposure is associated with no statistically resolved change in log real enterprise current environmental protection outlays (+0.0947 log points; clustered SE = 0.0869; bootstrap p = 0.3303) and statistically unresolved shifts in stationary pollutant capture shares (-0.0167; 95% bootstrap set [-0.0773, 0.0293]; p = 0.4876) and log captured tonnage (-0.0284; p = 0.8925). Conversely, relative compression in stationary emission intensity concentrates in the 2025 commencement year (-32.85 tonnes per billion 2020 tenge of real industrial output; SE = 13.37; bootstrap p = 0.0080; inverted 95% bootstrap set [-70.60, -8.91]; six-outcome within-phase Holm p = 0.0480; 24-test Holm p = 0.1920). This 2025 gradient strengthens without contemporaneous output controls (-56.79; bootstrap p = 0.0007) and persists across parent-clustered 17-region panels (-30.47; p = 0.0014), 2014–2016 anchors (-34.35; p = 0.0064), and directionally across all 16 single-region deletions (15 significant at 5%; Pavlodar omission p = 0.0660), while coexisting with pre-2020 downward exposure drift that bounds interpretation to conditional subnational convergence.

Keywords: industrial pollution regulation; enterprise abatement expenditure; integrated environmental permits; stationary atmospheric emissions; Kazakhstan; wild cluster bootstrap

1. Introduction

Environmental regulatory codes in industrializing and resource-intensive economies frequently sequence reform obligations across multi-year statutory calendars, separating initial monitoring and admin-

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istrative preparation from the scheduled commencement of integrated environmental permits and progressive emission-fee multipliers (Porter & Linde, 1995; Lange, 2006; Wilde, 2007; Stavins, 2020). Canonical models of firm abatement behavior predict that tightening compliance oversight and anticipated emission-charge schedules raise routine operating abatement expenditures and end-of-pipe pollutant capture at heavy-emitting installations (Rikun, 1992; Damania, 1996; Gautier, 2022). Yet empirical decompositions across manufacturing jurisdictions demonstrate that industrial emission intensities often decline without commensurate expansions in routine scrubber operating outlays, reflecting process modernization, fuel switching, capital vintage turnover, or intra-regional output reallocation (Jaffe & Palmer, 1997; Berman & Bui, 2001; Greenstone, 2002; Fowlie et al., 2012; Walker, 2013; Shapiro & Walker, 2018). Determining whether phased environmental codes operate through early routine operating outlays, end-of-pipe capture rates, or emission-intensity compression around scheduled permitting thresholds is central to regulatory design in heavy-industrial transition economies (Borgersen & King, 2016; Gulbrandsen et al., 2017; Shapiro & Walker, 2025).

Kazakhstan's Environmental Code No. 400-VI provides a structured subnational setting to evaluate these adjustment margins. Enacted on 2 January 2021 and entering into general force on 1 July 2021 under Article 416(1), the Code established a sequenced transition calendar (Parliament of the Republic of Kazakhstan, 2021). Between 2022 and 2024, preparatory compliance centered on best-available-technique reference audits, local environmental-budget earmarking, and mandatory installation of automated emission-monitoring systems at existing Category I facilities from 1 January 2023 (Article 418(16)). Under Article 418(4) and companion ministerial implementation schedules, 1 January 2025 marked both the scheduled commencement of the integrated environmental permit transition for Category I installations and the initial step of progressive emission-fee multipliers (scheduled at 2× in 2025, 4× in 2028, and 8× in 2031 for non-modernized major operators) (Parliament of the Republic of Kazakhstan, 2021; Ministry of Ecology, Geology and Natural Resources of the Republic of Kazakhstan, 2021; Assanov et al., 2021). Because coal-fired power generation, ferrous and non-ferrous metallurgy, and hydrocarbon extraction are spatially concentrated across Kazakhstan's oblasts, pre-reform stationary emission intensities differed by more than an order of magnitude across regions (Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan, 2026; Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan, 2026).

We construct a boundary-harmonized panel across all 16 consolidated parent regions of Kazakhstan from 2010 to 2025 ($N = 256$ region-years) from official Russian- and Kazakh-language statistical releases (Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan, 2025; Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan, 2026; Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan, 2026; Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan, 2026), aggregating additive physical tonnages and constant-2020-tenge monetary levels across the 2018 South Kazakhstan partition and the 2022 Abai, Zhetysu, and Ulytau splits prior to forming ratios or logarithms. We separate enterprise and organization current environmental protection outlays from subnational public budget spending, retain statistical confidentiality and source-dash cells as missing without zero imputation, and conduct finite-cluster inference across the 16 parent regions using 9,999 null-imposed restricted Rademacher wild cluster bootstrap replications with polynomial confidence-set inversion (Cameron et al., 2008; MacKinnon & Webb, 2018; Roodman et al., 2019; MacKinnon et al., 2023).

Three empirical findings emerge (detailed in Section 4.2 and Section 5). First, conditioning on parent-region fixed effects, calendar-year fixed effects, and log real industrial output, higher predetermined 2017–2019 stationary emission exposure yields no statistically resolved post-reform expansion in real enterprise current environmental protection outlays either during the 2022–2024 preparatory window

or in 2025 (pooled 2022–2025 slope +0.095 log points, bootstrap $p = 0.330$). Second, end-of-pipe capture metrics show statistically unresolved post-reform exposure gradients across both log captured tonnage and stationary capture shares. Third, relative compression in stationary atmospheric emission intensity concentrates in the 2025 commencement year (−32.85 tonnes per billion 2020 tenge per standard deviation of baseline exposure, bootstrap $p = 0.0080$, six-outcome within-phase Holm $p = 0.0480$, 24-test Holm $p = 0.1920$ (Holm, 1979)), strengthening when contemporaneous output scale is omitted from the right-hand side (−56.79, bootstrap $p = 0.0007$) and holding across 2018–2025 panels and 2014–2016 exposure anchors, while coexisting with pre-2020 downward exposure drift in the full 2010–2025 horizon that bounds interpretation to conditional subnational convergence. Companion Kazakh-language environmental capital-investment compendia for 2024 and 2025 further provide descriptive evidence of rising regional environmental capital-to-current expenditure ratios across disclosed jurisdictions (Section 5.1).

This study contributes to three strands of scholarship. Within environmental economics, it extends decompositions of industrial pollution declines across operating abatement expenditure, end-of-pipe capture, and production emission intensity (Jaffe & Palmer, 1997; Levinson & Taylor, 2008; Walker, 2013; Greenstone & Hanna, 2014; Shapiro & Walker, 2018; Andersson, 2019) to heavy-industrial transition settings governed by staggered statutory schedules (Tu & Shen, 2014; He & Ou, 2017; Wang & Yang, 2022; Zhang et al., 2024). Within institutional research on integrated best-available-technique permitting (Lange, 2006; Wilde, 2007), it evaluates how enterprise operating outlays and capital-to-current expenditure balances evolve as statutory permitting thresholds arrive. Within Central Asian environmental governance and extractive political economy (Netalieva et al., 2005; Gulbrandsen et al., 2017; Assanov et al., 2021), it provides a boundary-consistent 16-year subnational panel assessment of Kazakhstan's 2021 Environmental Code under small-cluster bootstrap inference.

2. Institutional Background and Analytical Framework

2.1. Phased Statutory Schedule of the 2021 Environmental Code

Kazakhstan's pre-2021 industrial air-quality framework relied on facility-specific maximum permissible emission permits paired with modest emission charges whose revenues flowed into general subnational budgets without inducing plant modernization in legacy coal-power and metallurgical complexes (Gulbrandsen et al., 2017; Assanov et al., 2021). Environmental Code No. 400-VI of 2 January 2021 reorganized stationary-source governance around the polluter-pays principle (Article 29) and integrated environmental permitting (Articles 111–130), sequencing statutory obligations across three distinct milestones in Articles 416–418 (Parliament of the Republic of Kazakhstan, 2021):

1. **Initial enactment and half-year transition (2021)**: Enacted on 2 January 2021, the Code entered into general force on 1 July 2021 under Article 416(1), creating a half-year operational transition during which facility risk classifications and best-available-technique reference procedures were established.
2. **Preparatory audit and automated-monitoring compliance phase (2022–2024)**: Over 2022–2024, statutory implementation centered on earmarking environmental payments to local environmental protection measures, conducting technological audits for best-available-technique reference handbooks, and enforcing mandatory automated emission-monitoring systems at existing Category I facilities from 1 January 2023 under Article 418(16) (Parliament of the Republic of Kazakhstan, 2021). Official ministerial explanations confirm that progressive nationwide 2×, 4×, and 8× emission-fee multipliers for non-transitioning major operators were scheduled for 2025, 2028, and 2031, so 2022–2024 represents preparatory monitoring and anticipation prior to scheduled multiplier onset (Ministry of Ecology, Geology and Natural Resources of the Republic of Kazakhstan, 2021).
3. **Scheduled integrated-permit and fee-multiplier commencement (2025)**: Under Article 418(4) and companion transitional schedules, 1 January 2025 marked the scheduled start of integrated en-

vironmental permitting for newly commissioned facilities and initial cohorts of Category I installations—alongside the first scheduled 2× fee-multiplier threshold for non-exempt operators outside approved modernization programs—with multi-year transition plans extending beyond 2025 for grandfathered plants (Parliament of the Republic of Kazakhstan, 2021; Ministry of Ecology, Geology and Natural Resources of the Republic of Kazakhstan, 2021).

Distinguishing these statutory windows is essential for empirical specification: 2021 captures partial-year commencement, 2022–2024 captures preparatory monitoring and technological audit compliance, and 2025 captures the initial commencement year of the scheduled integrated-permit and fee-escalation regime, although enterprise-level permit issuance and paid fee rates remain unobserved in regional aggregates.

2.2. Enterprise Abatement Margins and Falsifiable Hypotheses

Consider industrial installations in parent region r during year t producing real industrial output Q_{rt}^{R} and generating gross stationary atmospheric pollutants $G_{rt} = \gamma_{rt} Q_{rt}^{R}$, where the gross generation factor γ_{rt} reflects fuel mix, combustion efficiency, and equipment vintage. End-of-pipe abatement installations capture and neutralize tonnage $K_{rt} = s_{rt} G_{rt}$ ($s_{rt} \in [0, 1]$), leaving net atmospheric emissions $E_{rt} = (1 - s_{rt}) \gamma_{rt} Q_{rt}^{R}$ and regional stationary emission intensity $I_{rt} \equiv E_{rt} / Q_{rt}^{R} = (1 - s_{rt}) \gamma_{rt}$. Operating existing electrostatic precipitators, wet scrubbers, and monitoring equipment requires real enterprise current environmental protection outlays C_{rt}^{R}, whereas reducing gross generation γ_{rt} requires fixed-capital process modernization, fuel switching, or cleaner intra-regional capacity composition (Berman & Bui, 2001; Shapiro & Walker, 2018; Gautier, 2022).

Because statutory monitoring, permitting, and scheduled fee-multiplier obligations target heavy stationary emitters, regulatory exposure scales with a region's predetermined stationary emission intensity Z_r. Two falsifiable hypotheses follow:

- **Hypothesis 1 (Enterprise current abatement outlay gradient)**: If preparatory monitoring mandates (2022–2024) or the 2025 permit and fee-schedule commencement induce disproportionate routine operating compliance spending in historically emission-intensive regions, predetermined exposure Z_r will be positively associated with log real enterprise current outlays ($\log C_{rt}^{R}$) and real current outlays per generated tonne (C_{rt}^{R} / G_{rt}) conditional on industrial output.
- **Hypothesis 2 (End-of-pipe capture versus emission-intensity compression)**: If post-2021 emission reductions operate through intensified end-of-pipe scrubbing, higher Z_r will raise log captured tonnage ($\log K_{rt}$) and the capture share (s_{rt}); conversely, if adjustment concentrates around the 2025 commencement threshold via lower gross pollutant generation per unit of output without expanded scrubber operating shares, Z_r will exhibit negative conditional associations with emission intensity (I_{rt}) and log net emissions ($\log E_{rt}$) in 2025 alongside statistically flat capture shares.

3. Data, Boundary Harmonization, and Econometric Design

3.1. Official Statistical Series and Confidentiality Treatment

All subnational statistical series were compiled from official Russian- and Kazakh-language releases of the Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan published prior to the 13 November 2026 evidence cutoff (Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan, 2025; Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan, 2026; Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan, 2026; Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan, 2026). Three annual environmental series span 2010–2025: (i) net stationary-source at-

mospheric pollutant emissions (E_{rt}, thousand tonnes, updated 29 June 2026); (ii) stationary pollutants captured and neutralized by abatement installations (K_{rt}, thousand tonnes, updated 29 June 2026), yielding generated pollutants $G_{rt} = E_{rt} + K_{rt}$ and capture share $s_{rt} = K_{rt}/G_{rt}$; and (iii) current environmental protection expenditures of enterprises and organizations (C_{rt}, updated 13 July 2026, converted from source thousand-tenge tables to million tenge and deflated to constant 2020 prices via the chained national gross domestic product deflator, matching the 2025 national nominal total of 436,667.90 million tenge) (Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan, 2026). Regional industrial output Q^R_{rt} (updated 21 October 2026) and total fixed-capital investment (released 3 July 2026) are deflated to constant 2020 million tenge using chained annual-average national industrial producer-price and gross domestic product deflators (Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan, 2026). For descriptive capital benchmarking, we extract 2024 and 2025 regional environmental protection capital investments from separate official Kazakh-language annual investment compendia released on 4 July 2025 and 3 July 2026 (Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan, 2025; Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan, 2026).

Official statistical releases distinguish genuine numeric zeros from confidentiality suppressions and source dashes, and all confidential or dash cells are preserved as missing without imputation. In the consolidated 16-region panel ($N = 256$), net stationary emissions, real current enterprise outlays, and real industrial output are complete across all 256 cells. Captured stationary pollutants contain exactly one missing source dash in Atyrau in 2020 (leaving $N = 255$ for capture shares and outlays per generated tonne) and seven genuine numeric zero observations in Atyrau across 2015–2019, 2021, and 2023—with strictly positive capture recorded in 2010–2014, 2022, 2024, and 2025—yielding $N = 248$ for $\log K_{rt}$ and $N = 255$ under the zero-preserving inverse hyperbolic sine transformation.

3.2. Administrative Boundary Consolidation

Kazakhstan implemented two territorial reorganizations during 2010–2025: in June 2018, Shymkent City was separated from South Kazakhstan Oblast (renamed Turkestan Region), and in June 2022, Abai, Zhetysu, and Ulytau regions were carved out of East Kazakhstan, Almaty, and Karaganda oblasts. Deflating nominal monetary series prior to territorial summation and aggregating additive physical tonnages and constant-2020-tenge levels back into 16 time-consistent parent regions before forming ratios or logarithms eliminates artificial boundary breaks. A secondary 17-region panel over 2018–2025 ($N = 136$) retains Turkestan and Shymkent as separate cross-sectional units while consolidating the 2022 splits, evaluated both with 16-parent-region clustering under inherited South Kazakhstan exposure and with separate 2018–2019 successor-region anchors ($G = 17$).

3.3. Exposure Specification and Small-Cluster Bootstrap Inference

We define each parent region's predetermined exposure Z_r as the standardized 2017–2019 mean of $\log(E_{rt}/Q^R_{rt})$ across the 16 parent regions (zero mean, unit cross-regional variance), predating both the 2020 pandemic contraction and the January 2021 enactment of Code No. 400-VI. Our baseline phase-disaggregated regression estimates:

$$Y_{rt} = \alpha_r + \delta_t + \beta_1(Z_r \times \mathbf{1}\{t = 2021\}) + \beta_2(Z_r \times \mathbf{1}\{2022 \le t \le 2024\}) + \beta_3(Z_r \times \mathbf{1}\{t = 2025\}) + \gamma \log Q^R_{rt} + \varepsilon_{rt}, \quad (1)$$

paired with a pooled post-transition specification replacing the 2022–2024 and 2025 interactions with $\beta_{\text{post}}(Z_r \times \mathbf{1}\{2022 \le t \le 2025\})$ alongside $\beta_1(Z_r \times \mathbf{1}\{t = 2021\})$, and dynamic event-study regressions

interacting Z_r with individual year indicators normalized to zero in 2020 (de Chaisemartin & D'Haultfœuille, 2020). Parent-region fixed effects α_r absorb permanent industrial endowments, and year fixed effects δ_t absorb national macroeconomic and energy-price shocks. Because Q^R_{rt} enters the denominator of $I_{rt} \equiv E_{rt}/Q^R_{rt}$ and could respond endogenously or introduce division bias under measurement error, Section 5.2 re-estimates Equation (1) omitting $\log Q^R_{rt}$ entirely.

Because asymptotic cluster-robust t-tests over-reject with $G = 16$ clusters (Cameron et al., 2008; MacKinnon & Webb, 2018), we pair CR1 region-clustered standard errors with two-sided p-values and pointwise 95% confidence sets inverted from 9,999 null-imposed restricted Rademacher wild cluster bootstrap replications studentized by re-estimated CR1 standard errors (Roodman et al., 2019; MacKinnon et al., 2023). Every baseline specification produces a connected bounded 95% confidence set, and we report step-down Holm (1979) multiplicity-adjusted bootstrap p-values both within each statutory phase (six outcomes) and across the combined 24-coefficient family (four exposure terms × six outcomes).

4. Empirical Results

4.1. Subnational Summary Statistics and Exposure Concentration

Table 1 summarizes the 16-parent-region panel over 2010–2025. Real enterprise current environmental protection outlays average 13,533.96 million 2020 tenge per region-year (median 6,843.44 million), or 58,434.47 2020 tenge per tonne of generated stationary pollutants (median 12,899.95 tenge), reflecting wide dispersion between low-particulate hydrocarbon provinces and coal-metallurgical complexes generating millions of tonnes of flue ash and sulfur oxides. Captured and neutralized stationary pollutants average 1,908.98 thousand tonnes (median 500.10 thousand tonnes), corresponding to a mean capture share of 0.682 (median 0.871). Net stationary atmospheric emissions average 145.34 thousand tonnes per region-year (11.00 to 736.12 thousand tonnes), yielding a mean stationary emission intensity of 113.28 tonnes per billion 2020 tenge of real industrial output (median 72.67, maximum 516.27 in Pavlodar).

Table 1. Summary statistics for the consolidated 16-region Kazakhstan panel, 2010–2025.

Variable (unit)	*N*	Mean	SD	P25	Median	P75	Min	Max
Real enterprise current environmental outlays (mln 2020 KZT)	256	13,533.96	12,998.00	3,256.59	6,843.44	24,800.13	476.43	60,690.86
Real current outlays per generated tonne (2020 KZT/t)	255	58,434.47	96,337.94	3,500.22	12,899.95	78,685.43	504.14	548,246.25
Captured and neutralized pollutants (kt)	255	1,908.98	4,070.77	70.10	500.10	1,202.00	0.00	18,998.50
Stationary pollution capture share (proportion)	255	0.682	0.342	0.538	0.871	0.936	0.000	0.984
Net stationary atmospheric emissions (kt)	256	145.34	187.72	50.28	72.50	127.43	11.00	736.12
Stationary emission intensity (t/bn 2020 KZT)	256	113.28	111.26	34.80	72.67	140.37	11.07	516.27
Real regional industrial output (mln 2020 KZT)	256	1,630,858	1,437,661	695,739	1,300,042	1,985,885	150,696	7,922,291

(continued)

Table 1 (continued)

Variable (unit)	*N*	Mean	SD	P25	Median	P75	Min	Max
Real total fixed-capital investment (mln 2020 KZT)	256	695,840	564,540	368,064	560,173	785,160	113,559	4,510,022
Predetermined emission exposure, Z_r (SD, 2017–2019)	256	0.000	0.970	-0.690	0.006	0.552	-1.546	1.689
Predetermined mining output share (2017–2019)	224	0.390	0.340	0.118	0.199	0.805	0.013	0.909
Predetermined metallurgical output share (2017–2019)	208	0.198	0.204	0.016	0.101	0.410	0.002	0.568

Notes. Balanced parent-region grid covers 16 consolidated jurisdictions over 16 years ($N = 256$; industrial output and fixed-capital investment displayed to the nearest million 2020 KZT). Captured pollutants are missing in Atyrau in 2020 due to an official source dash ($N = 255$) and equal zero in Atyrau in 2015–2019, 2021, and 2023. Predetermined mining and metallurgical output shares are non-confidential across 14 ($N = 224$) and 13 ($N = 208$) parent regions, respectively ($n = 12$ regions jointly non-missing).

4.2. Phase-Disaggregated Exposure Gradients Across Abatement and Emissions

Table 2 and Figure 1 report our primary exposure-gradient regressions across all six expenditure, capture, and emission outcomes. Evaluating Hypothesis 1, high-exposure industrial regions exhibit no statistically resolved post-reform expansion in real enterprise current environmental protection outlays. In the log real outlay specification (Figure 1, Panel a), one standard deviation higher 2017–2019 emission exposure corresponds to +0.0897 log points in the 2021 half-year transition (bootstrap $p = 0.4771$), +0.1079 log points across the 2022–2024 preparatory monitoring window ($p = 0.2884$), +0.0511 log points in 2025 ($p = 0.5749$), and +0.0947 log points pooled across 2022–2025 (clustered standard error 0.0869, bootstrap $p = 0.3303$, inverted 95% bootstrap set $[-0.0865, 0.3558]$). Normalized per tonne of generated stationary pollutants, the point slope increases from +8,220.28 2020 tenge per tonne in 2021 to +14,069.32 in 2022–2024 and +20,964.85 in 2025 (standard error 11,965.76, bootstrap $p = 0.0907$, 95% bootstrap set $[-3{,}996.84, 56{,}133.22]$; pooled 2022–2025 estimate +15,668.63, $p = 0.3352$), remaining statistically unresolved at the 5% level across every window.

Table 2. Phase-disaggregated and pooled exposure-gradient regressions across enterprise abatement outlays, end-of-pipe capture, and stationary atmospheric emissions, 2010–2025.

Outcome variable (unit)	*N*	2021 (SE)/[*p*]	2022–24 (SE)/[*p*]	2025 (SE)/[*p*]	2022–25 (SE)/[*p*]	2025 CS
Log real current outlays (log mln 2020 KZT)	256	0.090 (0.102)/[0.477]	0.108 (0.090)/[0.288]	0.051 (0.090)/[0.575]	0.095 (0.087)/[0.330]	[-0.140, 0.295]
Real outlays per generated tonne (2020 KZT/t)	255	8,220 (14,429)/[0.515]	14,069 (16,401)/[0.446]	20,965 (11,966)/[0.091]	15,669 (14,831)/[0.335]	[-3,997, 56,133]
Log captured pollutants (log thousand t)	248	0.027 (0.139)/[0.842]	0.008 (0.207)/[0.969]	-0.144 (0.283)/[0.688]	-0.028 (0.215)/[0.893]	[-0.791, 0.428]
Stationary pollution capture share (prop.)	255	0.008 (0.012)/[0.529]	-0.013 (0.017)/[0.451]	-0.029 (0.039)/[0.535]	-0.017 (0.022)/[0.488]	[-0.137, 0.048]

(continued)

Table 2 (continued)

Outcome variable (unit)	*N*	2021 (SE)/[*p*]	2022–24 (SE)/[*p*]	2025 (SE)/[*p*]	2022–25 (SE)/[*p*]	2025 CS
Log net stationary emissions (log thousand t)	256	0.030 (0.079)/[0.782]	-0.005 (0.068)/[0.938]	-0.122 (0.060)/[0.077]	-0.032 (0.056)/[0.562]	[-0.255, 0.015]
Stationary emission intensity (t/bn 2020 KZT)	256	-18.36 (11.93)/[0.231]	-22.62 (14.38)/[0.175]	-32.85 (13.37)/[0.008]	-25.00 (13.98)/[0.054]	[-70.60, -8.91]

Notes. Each row summarizes two fixed-effects regressions on the 16-parent-region panel ($G = 16$ clusters): Equation (1) interacting standardized 2017–2019 log emission intensity (Z_r) separately with 2021, 2022–2024, and 2025 relative to 2010–2020, and a pooled model combining 2022–2025 while retaining a separate 2021 transition indicator. All specifications include parent-region fixed effects, calendar-year fixed effects, and log real regional industrial output. Parentheses report CR1 region-clustered standard errors; square brackets report two-sided null-imposed Rademacher wild cluster bootstrap *p*-values (9,999 replications); 2025 CS reports inverted 95% WCB confidence sets. For 2025 stationary emission intensity, Holm-adjusted bootstrap *p*-values are 0.0480 across the six 2025 outcomes and 0.1920 across all 24 phase-outcome coefficients.

End-of-pipe abatement capture responses are likewise negative in point terms and statistically unresolved (Figure 1, Panel b). Pooled 2022–2025 exposure interactions equal −0.0284 for log captured pollutants (bootstrap $p = 0.8925$, inverted 95% bootstrap set $[-0.5994, 0.3960]$; −0.1440 in 2025, $p = 0.6880$) and −0.0167 for the stationary pollution capture share (bootstrap $p = 0.4876$, 95% bootstrap set $[-0.0773, 0.0293]$; −0.0288 in 2025, $p = 0.5347$). Applying the inverse hyperbolic sine transformation to retain Atyrau's seven numeric zero observations ($N = 255$) yields a pooled slope of −0.1565 (clustered standard error 0.1591, bootstrap $p = 0.3665$, inverted 95% bootstrap set $[-0.6561, 0.1416]$). Although the confidence intervals do not rule out modest capture changes, the data provide no affirmative support for expanded end-of-pipe scrubbing shares in high-exposure regions.

Conversely, stationary atmospheric emission intensity displays progressive post-2021 compression that attains small-cluster statistical significance in the 2025 commencement year (Figure 1, Panel c). Relative to the 2010–2020 average baseline, one standard deviation higher predetermined exposure Z_r is associated with intensity differences of −18.36 tonnes per billion 2020 tenge in 2021 (bootstrap $p = 0.2307$), −22.62 across 2022–2024 ($p = 0.1753$), and −32.85 in 2025 (clustered standard error 13.37, conventional $p = 0.0266$, wild cluster bootstrap $p = 0.0080$, inverted 95% bootstrap set $[-70.60, -8.91]$). Benchmarked against the panel mean intensity of 113.28 tonnes per billion tenge, the 2025 gradient corresponds to a 29.0% relative compression per standard deviation of baseline exposure, remaining significant at the 5% level after step-down Holm adjustment across the six 2025 outcomes ($p_{\text{Holm},6} = 0.0480$), though widening to $p_{\text{Holm},24} = 0.1920$ under simultaneous adjustment across all 24 phase-by-outcome coefficients. In parallel, log net stationary emissions shift by −0.1220 log points in 2025 per standard deviation of Z_r (standard error 0.0598, conventional $p = 0.0593$, bootstrap $p = 0.0771$, 95% bootstrap set $[-0.2552, 0.0149]$), and the pooled 2022–2025 intensity slope stands at −25.00 tonnes per billion tenge (bootstrap $p = 0.0540$). Measured relative to the single pre-enactment reference year 2020 in the event study, the 2025 exposure differential equals −22.49 tonnes per billion tenge (bootstrap $p = 0.0030$) for emission intensity and −0.1633 log points ($p = 0.0277$) for log net emissions.

5. Industrial Mechanisms, Capital Retooling Benchmarks, and Sensitivity Analysis

5.1. Industrial Archetype Heterogeneity and Descriptive Capital Outlays

Figure 2 characterizes subnational emission distributions across regional industrial archetypes. Comparing regional mean stationary emission intensity in 2022–2025 against the immediate pre-reform

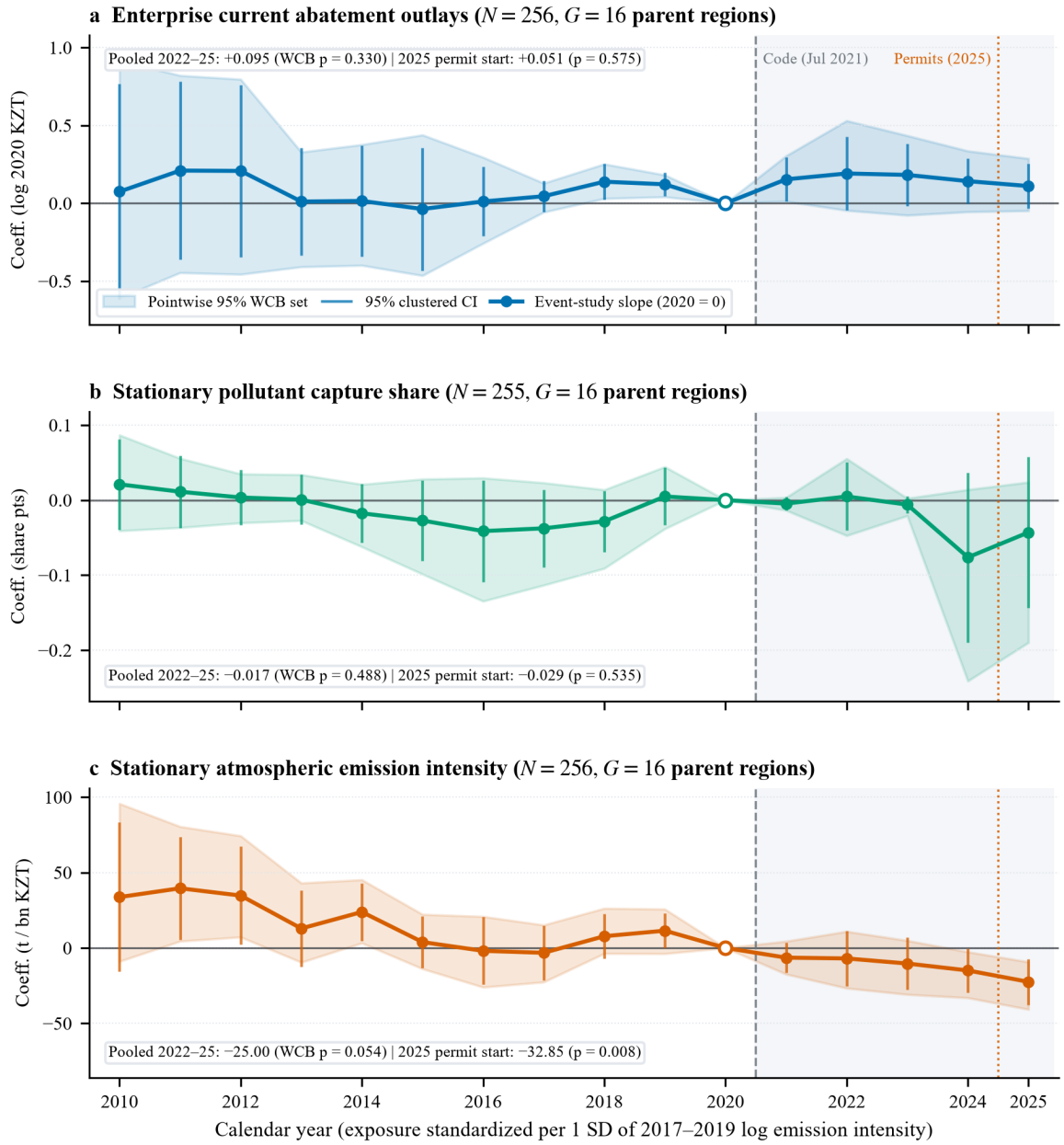


Figure 1. Dynamic exposure-gradient event studies across enterprise outlays, pollutant capture, and emission intensity.

Notes. Panels a–c plot dynamic year-specific interactions of standardized 2017–2019 regional stationary emission exposure (Z_r) with calendar-year indicators from 2010 to 2025 (normalized to zero in 2020), controlling for parent-region fixed effects, year fixed effects, and log real industrial output ($G = 16$). Vertical whiskers denote 95% CR1 cluster-robust confidence intervals; shaded bands trace pointwise 95% confidence sets inverted from 9,999 null-imposed Rademacher wild cluster bootstrap draws; inset boxes report period-regression estimates benchmarked against 2010–2020. Dashed and dotted vertical lines mark general commencement of the Environmental Code (July 2021) and scheduled commencement of Category I integrated permitting and fee multipliers (January 2025).

2017–2020 window across the 16 parent regions (Figure 2, Panel a) yields an unweighted cross-regional ordinary least squares slope of −25.95 tonnes per billion 2020 tenge per standard deviation of Z_r (R^2 = 0.461; comparing 2022–2025 against the full 2010–2020 pre-period yields an even steeper slope of −43.01 tonnes per billion tenge, R^2 = 0.483), led by consolidated Karaganda (−59.37 vs. 2017–2020), North Kazakhstan (−142.64), Kostanay (−49.03), and Akmola (−48.26), whereas Pavlodar exhibits minimal unconditional change (−2.76). Across the empirical cumulative distribution (Figure 2, Panel b), regional emission intensity shifts leftward between 2010–2020 (N = 176, median 71.9, 90th percentile 273 tonnes per billion tenge) and 2022–2025 (N = 64, median 50.2, 90th percentile 174 tonnes per billion tenge), while the three coal and metallurgical parent regions continuously account for 55.7% to 62.7% of national net stationary tonnage (Figure 2, Panel c).

Table 3 evaluates whether pooled 2022–2025 exposure slopes differ across coal-metallurgical (n = 3) and western oil-and-gas (n = 4) parent regions relative to the remaining nine diversified regions, and documents the 2024–2025 environmental capital-investment cross-sections. With few regions per industrial group, subgroup slope differentials carry wide confidence intervals: individual differential bootstrap p-values are at least 0.1263, and joint wild cluster bootstrap tests of equal subgroup exposure slopes across all three groups yield p-values ranging from 0.3334 (log current outlays) to 0.8133 (capture share; 0.7022 for emission intensity). Consequently, between-archetype heterogeneity remains statistically unresolved in regional aggregates.

Table 3. Industrial subgroup heterogeneity regressions (2010–2025) and descriptive environmental capital-to-current expenditure benchmarks (2024–2025).

Subgroup interaction model (unit)	N	Ref. Post	Coal/Met. Diff.	Oil/Gas Diff.
Log real current outlays (log mln 2020 KZT)	256	0.137 (0.080)/[0.226]	-0.212 (0.095)/[0.126]	0.090 (0.280)/[0.780]
Real outlays per generated tonne (2020 KZT/t)	255	1,467 (7,895)/[0.861]	-2,303 (9,991)/[0.826]	31,006 (51,752)/[0.726]
Log captured pollutants (log thousand t)	248	-0.008 (0.345)/[0.980]	0.206 (0.331)/[0.561]	0.143 (0.660)/[0.832]
Stationary pollution capture share (prop.)	255	-0.019 (0.029)/[0.467]	0.016 (0.031)/[0.607]	0.042 (0.070)/[0.551]
Log net stationary emissions (log thousand t)	256	-0.083 (0.105)/[0.497]	0.166 (0.112)/[0.284]	0.036 (0.142)/[0.822]
Stationary emission intensity (t/bn 2020 KZT)	256	-48.21 (25.87)/[0.398]	27.87 (30.11)/[0.572]	42.43 (25.30)/[0.450]

Notes. Regressions on G = 16 parent-region clusters augment the pooled 2022–2025 model (controlling for parent-region fixed effects, year fixed effects, log real industrial output, and the common 2021 transition-exposure interaction) with subgroup-specific pooled-post level indicators and differential post-reform exposure slopes for coal-metallurgical (n = 3: Pavlodar, consolidated Karaganda, consolidated East Kazakhstan) and western oil-gas (n = 4: Atyrau, Mangystau, West Kazakhstan, Aktobe) regions relative to the nine diversified reference regions (Ref. Post); parentheses report CR1 standard errors, brackets report WCB p-values, and joint two-restriction subgroup heterogeneity WCB p-values span 0.3334 to 0.8133. In the companion descriptive environmental capital-investment cross-sections (Figure 3, Panel c), non-confidential nominal environmental protection capital outlays are observed in n = 12 parent regions in 2024 (aggregate 105,974.2 million current tenge; all-observed median capital-to-current outlay ratio 0.1806; Spearman rank correlation between capital and current outlays ρ = 0.783) and n = 8 parent regions in 2025 (aggregate 242,627.9 million current tenge; all-observed median ratio 0.8535; Spearman ρ = 0.286). Across the n = 7 matched parent regions disclosed in both years, nominal environmental capital outlays rose by 167.6% from 74,768.9 to 200,061.5 million tenge and the paired median capital-to-current ratio increased from 0.1707 to 0.6911.

Verified Kazakh-language annual investment compendia for 2024 and 2025 (Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan, 2025; Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kaza-

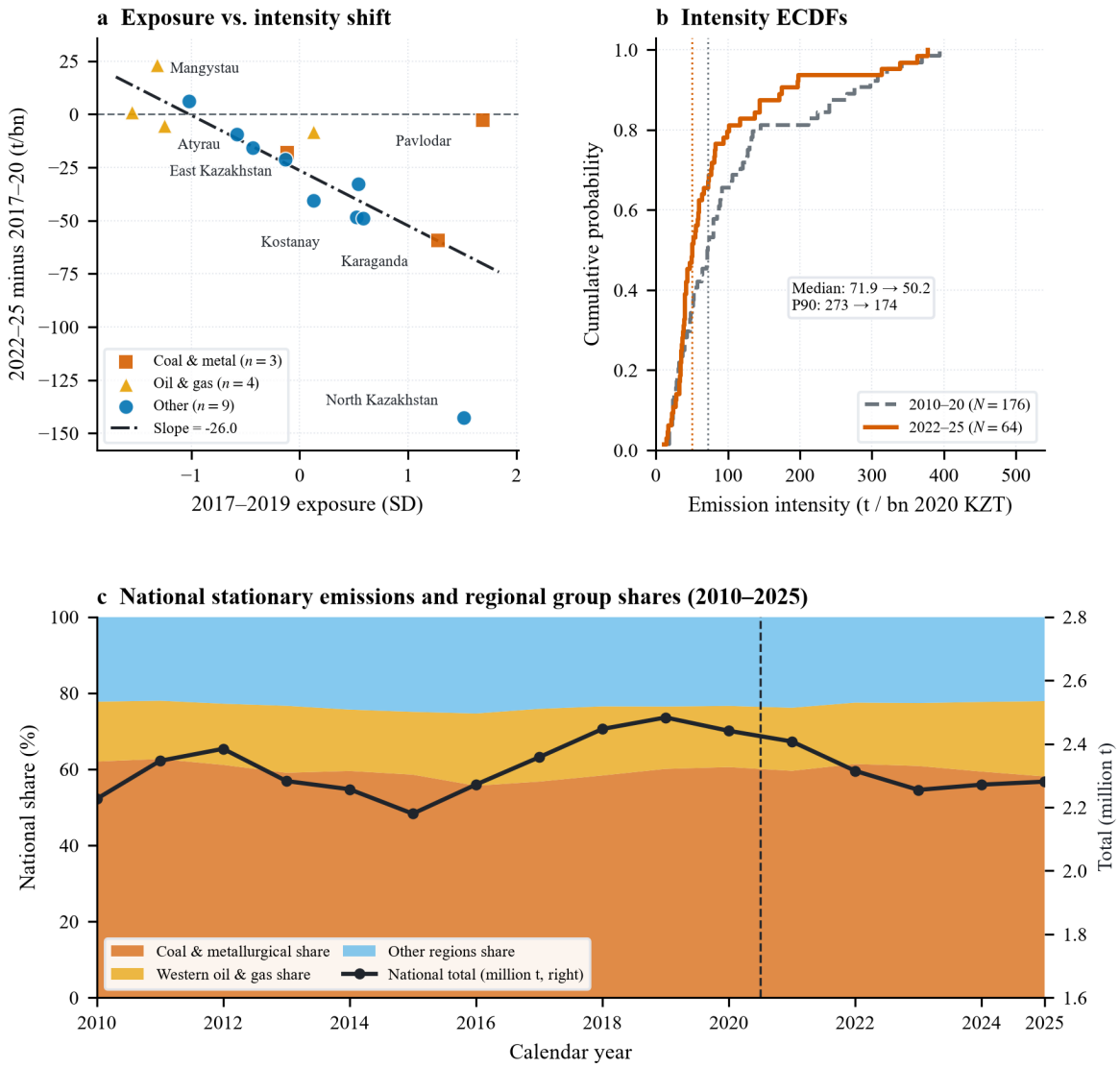


Figure 2. Subnational exposure scatter, empirical intensity distributions, and regional-group emission shares.

Notes. Panel a plots regional post-reform (2022–2025) minus immediate pre-reform (2017–2020) mean stationary emission intensity against standardized 2017–2019 log emission intensity exposure across $n = 16$ consolidated parent regions (OLS slope −25.95, $R^2 = 0.461$; using 2010–2020 as pre-period gives slope −43.01, $R^2 = 0.483$). Panel b compares 2010–2020 ($N = 176$) and 2022–2025 ($N = 64$) empirical cumulative distributions of regional stationary emission intensity. Panel c displays stacked shares of national net stationary atmospheric emissions across coal and metallurgical ($n = 3$), western oil and gas ($n = 4$), and other ($n = 9$) parent regions alongside aggregate national stationary emissions on the right axis.

khstan, 2026) provide descriptive context for why regional emission intensity compressed in 2025 without a concomitant surge in current abatement spending (Figure 3, Panel c). Whereas enterprise current outlays measure routine operation of existing scrubbers across environmental media, fixed-capital outlays finance boiler retrofits, gas-recovery units, and cleaner production equipment across environmental functions. Among all disclosed parent regions, observed nominal environmental capital investment totaled 105,974.2 million tenge across 12 regions in 2024 (median capital-to-current ratio 0.1806) and 242,627.9 million tenge across eight regions in 2025 (median ratio 0.8535). Restricting comparison strictly to the seven matched parent regions non-confidential in both years, aggregate nominal environmental capital formation expanded by 167.6% (74,768.9 to 200,061.5 million tenge) and the paired median capital-to-

current ratio quadrupled from 0.1707 to 0.6911—a descriptive pattern consistent with capital-embodied preparation around 2025, though unlinked to plant-level best-available-technique permits.

5.2. Scale-Free Specifications, Boundary Clustering, Composition Trends, and Pretrend Diagnostics

Table 4 and Figure 3 (Panels a–b) subject the emission-intensity results to five econometric diagnostics addressing endogenous output controls, successor-region clustering, exposure-anchor timing, sectoral trend interactions, and pre-reform convergence. First, because Q_{rt}^{R} forms the denominator of I_{rt}, conditioning on $\log Q_{rt}^{R}$ in Equation (1) could induce division bias or absorb scale-mediated compliance. Re-estimating Equation (1) without $\log Q_{rt}^{R}$ strengthens the negative exposure gradient across all three statutory phases: −33.87 tonnes per billion 2020 tenge in 2021 (bootstrap $p = 0.0143$), −38.42 in 2022–2024 ($p = 0.0378$), and −56.79 in 2025 (CR1 standard error 16.06, bootstrap $p = 0.0007$, inverted 95% bootstrap set $[-95.41, -20.07]$), while scale-free 2025 log net emissions equal −0.1138 ($p = 0.0942$) and capture share (−0.0433, $p = 0.5386$) and log outlays (+0.2075, $p = 0.1803$) remain unresolved.

Second, in the 17-region 2018–2025 panel ($N = 136$) where Turkestan and Shymkent enter separately, clustering at the 16-parent-region level to account for their shared consolidated South Kazakhstan exposure yields −20.46 pooled across 2022–2025 (bootstrap $p = 0.0013$) and −30.47 in 2025 ($p = 0.0014$, 95% set $[-56.22, -16.23]$); assigning Turkestan and Shymkent separate 2018–2019 mean-log anchors ($G = 17$) yields −20.51 pooled ($p = 0.0006$) and −30.51 in 2025 ($p = 0.0019$; −29.58, $p = 0.0023$ when all 17 regions use synchronized 2018–2019 anchors), matching the 16-parent-region panel on 2018–2025 (−20.12 pooled, $p = 0.0023$). Third, anchoring predetermined exposure to 2014–2016 over 2010–2025 ($N = 256$) yields −26.91 pooled ($p = 0.0406$) and −34.35 in 2025 ($p = 0.0064$). Fourth, on the 12-region non-confidential sectoral subsample ($N = 192, G = 12$), adding three parametric controls—predetermined 2017–2019 mining share × linear year trend, metallurgical share × linear year trend, and mining share × log national domestic crude-oil and natural-gas producer price index—preserves the 2025 point magnitude at −33.44 (widening bootstrap p to 0.1300 with $G = 12$ clusters). Fifth, across all 16 leave-one-region-out deletions (Figure 3, Panel a), the 2025 intensity estimate stays between −41.23 (omitting Pavlodar, bootstrap $p = 0.0660$, 95% set $[-79.12, 2.20]$) and −21.50 (omitting North Kazakhstan, $p = 0.0405$), passing the 5% bootstrap threshold in 15 of 16 runs.

Table 4. Scale-free, boundary-clustering, exposure-anchor, sectoral-trend, and pre-reform placebo diagnostics.

Diagnostic or sensitivity check	N, G	Parameter	Estimate (SE)	WCB p	95% CS
Baseline 16 parent regions, 2010–2025	256, 16	2025 (Z_r)	-32.85 (13.37)	0.0080	[-70.60, -8.91]
Omit industrial output control ($\log Q_{rt}^{R}$)	256, 16	2025 (Z_r)	-56.79 (16.06)	0.0007	[-95.41, -20.07]
Omit industrial output control ($\log Q_{rt}^{R}$)	256, 16	2022–24 (Z_r)	-38.42 (16.67)	0.0378	[-79.63, -1.98]
17 regions, parent-cluster inference (2018–2025)	136, 16	2025 (Z_r)	-30.47 (8.68)	0.0014	[-56.22, -16.23]
17 regions, separate split anchors (2018–2025)	136, 17	2025 (Z_r^{split})	-30.51 (8.64)	0.0019	[-56.00, -16.20]
Matched 16 parent regions, 2018–2025	128, 16	2022–25 (Z_r)	-20.12 (9.17)	0.0023	[-47.63, -5.70]
Earlier 2014–2016 exposure anchor	256, 16	2025 (Z_r^{14-16})	-34.35 (13.24)	0.0064	[-71.55, -9.75]

(continued)

Table 4 (continued)

Diagnostic or sensitivity check	N, G	Parameter	Estimate (SE)	WCB p	95% CS
Sectoral linear trends & oil/gas PPI interaction	192, 12	2025 (Z_r)	-33.44 (19.14)	0.1300	[-90.79, 7.69]
Look-ahead-free 2016 placebo (2013–2015 anchor)	176, 16	2016–20 (Z_r^{13-15})	-24.87 (7.32)	0.0220	[-42.79, -7.83]
Pre-reform linear exposure trend (2010–2020)	176, 16	Linear trend	-3.49 (1.73)	0.0688	[-8.09, 0.42]
Joint event-study pretrend test (2010–2019)	256, 16	Wald $F = 5.57$	—	0.7302	—
Leave-one-region-out envelope (2025)	240, 15	16-run range	[-41.23, -21.50]	≤ 0.0660	15/16 sig.
Inverse hyperbolic sine captured tonnage	255, 16	2022–25 (Z_r)	-0.157 (0.159)	0.3665	[-0.656, 0.142]

Notes. All rows except the final row evaluate stationary emission intensity (tonnes per billion 2020 tenge of real industrial output); the final row evaluates inverse-hyperbolic-sine captured stationary pollutants retaining all seven numeric zero observations in Atyrau (2015–2019, 2021, 2023). Parameter column indicates the statutory window interacted with standardized baseline exposure; 95% CS reports inverted WCB confidence sets (15 of 16 leave-one-out sets exclude zero). The look-ahead-free 2016 placebo anchors exposure strictly prior to 2016 using standardized 2013–2015 mean log intensity over the 2010–2020 pre-reform sample (using 2017–2019 exposure yields −19.26, WCB $p = 0.0824$). Joint event-study pretrend tests evaluate the 10 pre-2020 leads simultaneously via 9,999 null-imposed wild cluster bootstrap draws (conventional cluster Wald $p = 0.0016$ vs. bootstrap $p = 0.7302$).

Pre-reform trajectory diagnostics clarify why our estimates measure conditional convergence instead of a standalone treatment effect over the 16-year horizon. Although joint 10-lead wild cluster bootstrap tests over 2010–2019 do not reject zero across the six outcomes ($p = 0.4206$ to 0.9883, reflecting limited finite-cluster power when testing 10 restrictions across $G = 16$ clusters), pointwise early-decade emission-intensity leads in 2011 ($p = 0.0286$), 2012 ($p = 0.0058$), and 2014 ($p = 0.0328$) are positive relative to 2020 (Figure 1, Panel c). Over 2010–2020, high-Z_r regions exhibited a linear downward drift of −3.49 tonnes per billion tenge per year (bootstrap $p = 0.0688$)—whose decadal projection from the 2015 baseline midpoint approaches the 2025 coefficient—and a strictly pre-dated 2016–2020 placebo anchored on 2013–2015 mean log intensity yields −24.87 tonnes per billion tenge (bootstrap $p = 0.0220$; −27.76, $p = 0.0087$ under arithmetic-mean intensity anchoring), whereas pre-2016 placebos for log emissions ($p = 0.4033$), capture share ($p = 0.0981$), and log outlays ($p = 0.9872$) remain statistically flat. Within the shorter 2018–2025 sample where pre-2018 early-decade convergence is excluded and 2018–2020 leads are flat, the sharp step-down in 2025 relative to 2022–2024 remains highly significant (−30.47 vs. −17.94 under parent clustering, bootstrap $p = 0.0014$).

5.3. Methodological Scope and Limitations

Four scope conditions govern interpretation. First, because Code No. 400-VI took effect nationwide alongside pre-2018 subnational intensity convergence, exposure-gradient regressions identify conditional convergence associations across statutory phases and cannot isolate causal effects of individual statutory provisions from ongoing structural modernization. Second, statutory phase boundaries follow enacted Code No. 400-VI and official 2021 ministerial explanations without observing facility-specific permit approvals, exemptions, or effective tax payments. Third, absence of publicly linked facility-level integrated-permit registries, continuous emission-monitoring feeds, and enterprise balance sheets precludes decomposing regional intensity declines between within-plant process retrofits and intra-regional

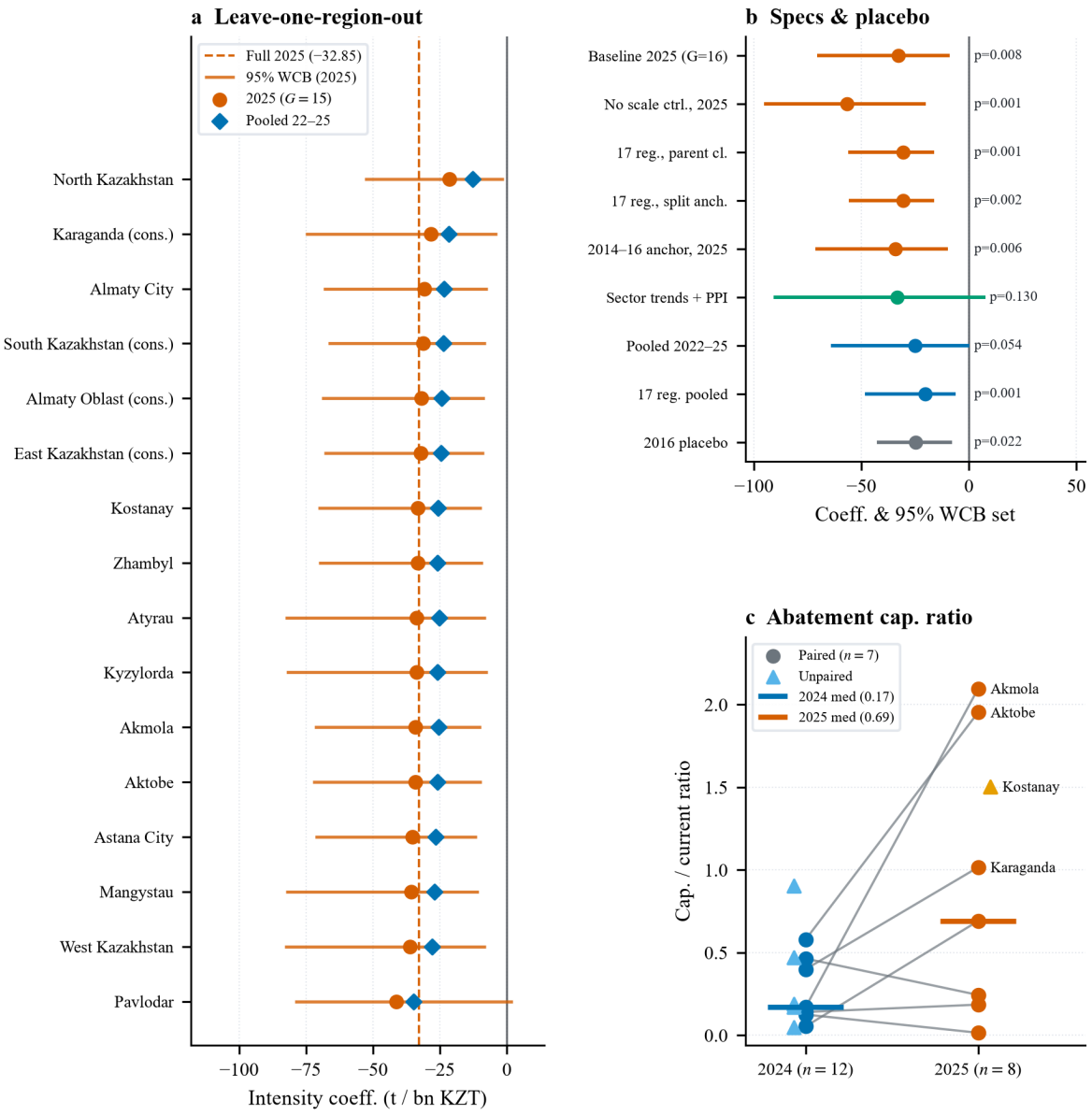


Figure 3. Leave-one-region-out stability, specification diagnostics, and environmental capital-to-current outlay ratios.

Notes. Panel a plots 2025 commencement estimates (circles with pointwise 95% inverted wild cluster bootstrap sets) and pooled 2022–2025 estimates (diamonds) for stationary emission intensity across all 16 single-region deletions ($N = 240, G = 15$). Panel b compares baseline, scale-free (omitting log Q_{rt}^{R}), 17-region parent-clustered and split-anchor, 2014–2016 anchor, sectoral linear-trend, and look-ahead-free 2016 placebo (2013–2015 anchor) models with two-sided bootstrap p-values. Panel c plots observed regional ratios of nominal environmental protection capital investment to current enterprise environmental outlays in 2024 ($n = 12$) and 2025 ($n = 8$), distinguishing the $n = 7$ paired parent regions (circles connected by lines) from unpaired disclosed regions (triangles).

output reallocation across plants. Fourth, confidentiality suppressions restrict 2024–2025 environmental capital-investment cross-sections to 12 and eight parent regions (seven paired) across multi-media environmental functions, making the capital-to-current benchmark strictly descriptive.

6. Conclusion and Policy Implications

Across a boundary-harmonized panel of Kazakhstan's 16 consolidated parent regions from 2010 to 2025, neither the 2022–2024 preparatory monitoring window of Environmental Code No. 400-VI nor the 2025 commencement of Category I integrated permitting and scheduled fee multipliers produced a statistically resolved expansion in enterprise current environmental protection outlays or end-of-pipe pollutant capture shares in historically emission-intensive industrial regions. Instead, conditional compression in stationary atmospheric emission intensity sharpened in the 2025 commencement year—holding across scale-free specifications, parent-clustered and split-anchor 2018–2025 panels, and earlier exposure anchors while coexisting with pre-2018 secular convergence—alongside a descriptive 167.6% expansion in nominal environmental capital outlays across matched non-confidential regions between 2024 and 2025.

These findings motivate two concrete institutional reforms for environmental governance in heavy-industrial transition economies. First, tracking routine enterprise current environmental outlays or aggregate end-of-pipe capture shares alone fails to detect capital-embodied compliance preparation around integrated-permit and fee-escalation thresholds; regulatory evaluation frameworks should pair continuous emission-intensity benchmarks with audited capital-modernization milestones under best-available-technique transition programs. Second, Kazakhstan's Ministry of Ecology and Natural Resources and Bureau of National Statistics should link Category I automated emission-monitoring disclosures, integrated-permit registries, and enterprise-level pollution-charge receipts with regional environmental capital-formation accounts while narrowing confidentiality suppressions in subnational capital tables, enabling transparent verification of plant-level modernization across Central Asia's industrial heartlands.

Statements

Data availability. Regional atmospheric emission inventories, enterprise environmental protection expenditure accounts, industrial production series, and statutory texts of the 2021 Environmental Code originate from official publications of the Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan, the Parliament of the Republic of Kazakhstan, and the Official Information Resource of the Prime Minister of the Republic of Kazakhstan. Boundary-harmonized regional datasets, archived statistical inputs, and full replication code are deposited in Zenodo at https://doi.org/10.5281/zenodo.24199870.

AI declaration. In preparing this article, OpenAI Codex was used solely to support the translation and proofreading of Russian- and Kazakh-language statistical and legal documents, routine data cleaning, and implementation-level verification of the estimation code. All authors independently inspected and verified these auxiliary outputs, completed every other aspect of the research, and assume full responsibility for the final text.

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