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REGIONAL HEALTH AND SOCIAL INDICATOR PATTERNS AND PCA-BASED MORTALITY MODELING IN KAZAKHSTAN, 2011–2024. A TWO-PART EXPLORATORY ECOLOGICAL ANALYSIS

Abstract. Objective. To compare five regional health and social indicators between project-defined exposed and comparison regions, and to test whether PCA can reduce five predictors to two components without greatly reducing mortality-model fit. **Methods.** Data from 2011–2024 were analyzed in two parts. RQ1 compared six regions and included a pre-2022 check for boundary changes. RQ2 used three exposed-classified regions and compared a region-and-year baseline OLS model with a five-indicator model and a PC1+PC2 model. **Results.** PC1 and PC2 retained 75.21% of predictor variance. R^2 was 0.084 for the baseline model, 0.311 for the five-indicator model, and 0.264 for the PCA model. The PCA model had the best adjusted R^2, AIC, and BIC. **Conclusion.** PCA gave a simpler model with limited loss of fit. Group differences are descriptive and do not prove a radiation effect.

Keywords: Kazakhstan; Semipalatinsk; principal component analysis; ecological study; regional health indicators; mortality.

1. Introduction

1.1. Historical context

The Semipalatinsk Nuclear Test Site (SNTS) was a major Soviet nuclear testing site. About 456 nuclear explosions were carried out there between 1949 and 1989, and the site was closed in 1991 [1, 2]. Earlier health studies near SNTS used information such as place of residence, settlement history, and estimated radiation dose [3, 4, 5, 6]. These studies provide important background, but they also show why present-day region labels cannot be treated as direct measures of past radiation exposure.

This study does not try to prove that radiation caused the observed regional differences. Instead, it uses regional statistics to describe long-term health and social patterns and to test whether PCA can simplify the predictor set. Any group differences are treated as regional patterns only.

1.2. Study aims and research questions

The study has two related questions. RQ1 asks how five regional health and social indicators differ between project-defined exposed and comparison regions during 2011–2024. RQ2 uses only the exposed-classified regions and asks whether five indicators can be reduced to PC1 and PC2 with only a small loss of fit when modeling crude all-cause mortality. Mortality is not included in PCA; it is used only as the outcome in the regression models.

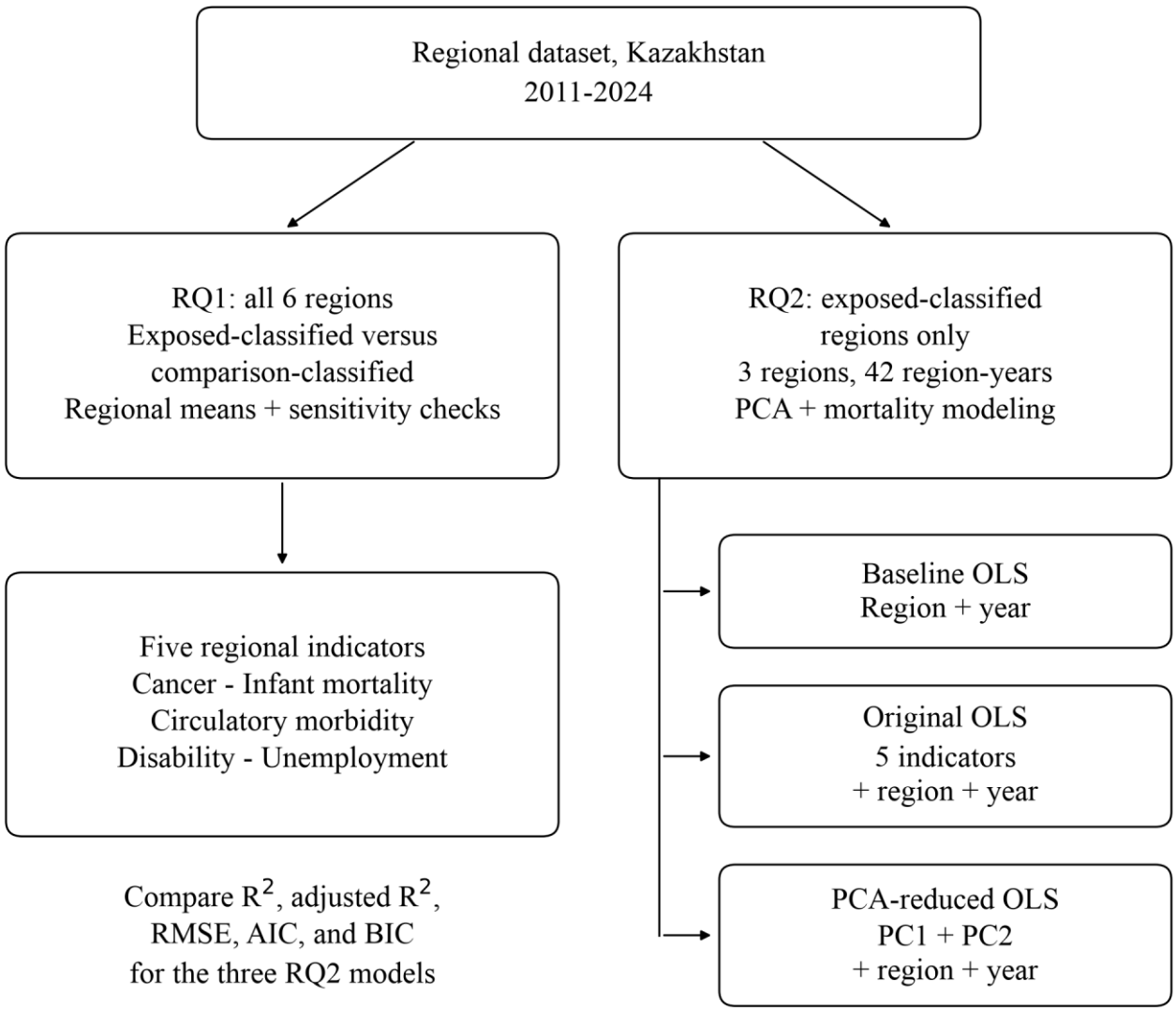


Figure 1 – Study design. RQ1 compares all six regions. RQ2 uses only the three exposed-classified regions and compares a baseline model, a five-indicator model, and a PCA-based model.

2. Methods

2.1. Study design and region selection

This regional panel study covers 2011–2024 [7, 8, 9]. For RQ1, six regions were observed for 14 years, giving 84 region-year rows. East Kazakhstan+Abay, Karaganda, and Pavlodar were chosen as the exposed-classified group because they were the exposed regions in the original project design. Akmola, Almaty Region, and Kostanay were used as comparison regions because they were outside that project classification and the same annual indicators were available for the study period. They are a comparison set, not a matched control group, and the classification is not based on measured radiation dose.

RQ2 uses only the three exposed-classified regions, giving 42 region-year rows. Standardization, KMO and Bartlett tests, PCA coefficients, PC scores, and the regression models are all recalculated using this exposed-only sample.

2.2. Variables, denominators, and outcome construction

Table 1 – Variables, source units, and transformations. The indicators use different denominators; standardization puts them on a common statistical scale for PCA.

Variable	Role	Source unit	Analytical form
Cancer morbidity	Predictor	Cases per 100,000 population	Divide by 1,000; report as %
Infant mortality	Predictor	Deaths under age 1 per 1,000 live births	Divide by 10; % of live births
Circulatory-disease morbidity	Predictor	Cases per 100,000 population	Divide by 1,000; report as %
Registered disability	Predictor	Registered persons	Count / population × 100
Unemployment	Predictor	% of labor force	Retain reported percentage
Crude all-cause mortality	RQ2 observed outcome	Registered deaths	Deaths / population × 100

Crude all-cause mortality is an observed outcome calculated for each region and year from registered deaths divided by population. The OLS models then calculate fitted mortality values. Registered deaths are therefore source data, not predictions.

2.3. Data audit and administrative-boundary handling

Before the main analysis, the data were checked again. Mortality was recalculated for every region-year as registered deaths divided by population. This replaced an earlier working mortality series that did not match the supplied death counts. A 2015 unemployment reading error was also corrected after the header “20152)” had been read as year 20152 instead of 2015.

Regional borders changed in 2022 when Abay, Zhetysu, and Ulytau were created. This affected East Kazakhstan, Almaty Region, and Karaganda. For mortality, death counts were combined in the same way as the population series used in the project. East Kazakhstan and Abay were combined for the East Kazakhstan+Abay unit. Karaganda and Ulytau were combined where needed before the split. For some rate-based indicators, the supplied files did not contain all denominators needed to fully rebuild the new borders. To check whether this matters, the study also repeats the main comparisons using only 2011–2021, before the reform.

2.4. RQ1: regional comparison

For each indicator, a 14-year mean was first calculated for each region. Group means were then calculated from the three regional means in each class. This avoids treating repeated yearly values as 84 independent regions. Because there are only six regions, statistical testing is limited. An exact permutation check was used as a sensitivity analysis, and the same comparison was repeated for 2011–2021 to check the effect of the 2022 border changes.

2.5. RQ2: PCA and mortality models

For RQ2, cancer morbidity, infant mortality, circulatory-disease morbidity, registered disability, and unemployment were standardized within the 42 exposed-region observations. KMO and Bartlett tests were used to check whether PCA was reasonable [10]. Because the same regions are observed repeatedly over time, the usual Bartlett p value is only approximate. Mortality was not used to build the components. PC1 and PC2 were kept and are described simply as principal components, not as a vulnerability index.

Three OLS models were compared using the same 42 observations. The baseline model used only region and a linear year trend. The original-indicator model added the five observed predictors. The PCA model used PC1 and PC2 instead of the five predictors. HC3 standard errors were used as an extra check on coefficient uncertainty [11], but HC3 does not change fitted values and does not correct for repeated observations within a region. The models were compared using R^2, adjusted R^2, RMSE, AIC, and BIC. All of these results are in-sample.

3. Results

3.1. RQ1: exposed-classified versus comparison-classified regions

Table 2 – RQ1 comparison based on six regional means. Exact permutation values are exploratory because the groups were not randomly assigned.

Indicator	Exposed mean	Comparison mean	Difference	Exact p
Cancer morbidity	0.2932	0.2259	+0.0673	0.20
Infant mortality	0.8715	0.9162	−0.0447	0.60
Circulatory morbidity	2.6673	2.4730	+0.1943	0.60
Registered disability	4.1861	3.9418	+0.2443	0.80
Unemployment	4.8362	4.8857	−0.0496	0.50

The exposed-classified group had higher average cancer morbidity, circulatory morbidity, and registered disability. Infant mortality and unemployment were slightly lower. The exact six-region permutation checks did not show strong group separation. These results should therefore be read as descriptive regional differences, not as evidence of a radiation effect.

3.2. Sensitivity to the 2022 administrative reforms

Table 3 – Difference in group means (exposed-classified minus comparison-classified) for 2011–2024 and for the pre-reform period 2011–2021.

Indicator	2011–2024 difference	2011–2021 difference
Cancer morbidity	+0.0673	+0.0619
Infant mortality	−0.0447	−0.0251
Circulatory morbidity	+0.1943	+0.1264
Registered disability	+0.2443	+0.0646
Unemployment	−0.0496	−0.0182

The direction of the differences in cancer, infant mortality, circulatory disease, and unemployment stayed similar before 2022. The disability difference became much smaller in the 2011–2021 analysis. This shows that the full-period disability result is sensitive to the 2022 border changes.

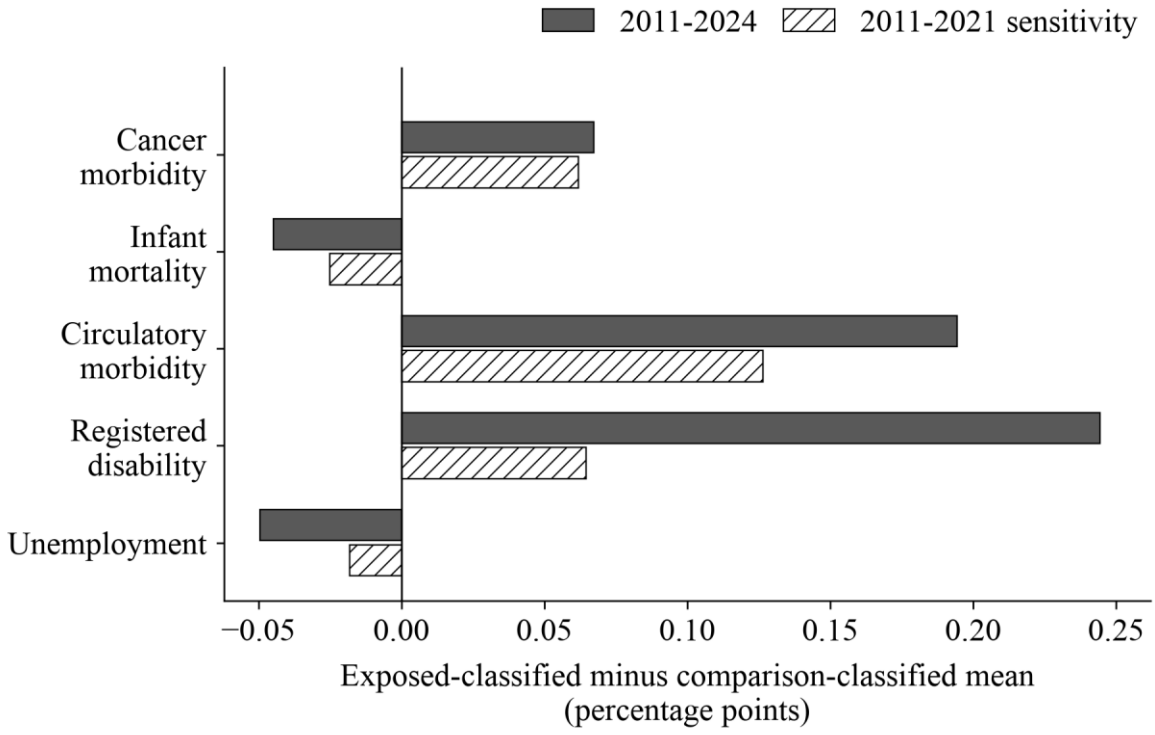


Figure 2 – RQ1 group differences for the full period compared with the 2011–2021 pre-reform period.

3.3. PCA suitability and component structure

In the exposed-only sample, overall KMO was 0.5099, which is only just acceptable for exploratory PCA. Bartlett's test gave $\chi^2(10) = 75.56$ with a conventional $p < 0.001$. PC1 explained 49.18% of predictor variance and PC2 explained 26.03%, so together they retained 75.21%. The KMO for disability was very low (0.216), so the PCA results should be treated as exploratory.

Table 4 – PCA coefficients for the exposed-only sample. Positive and negative signs show that the components combine the indicators in different directions.

Indicator	PC1 coefficient	PC2 coefficient
Cancer morbidity	−0.450	−0.389
Infant mortality	+0.513	−0.027
Circulatory morbidity	−0.465	−0.193
Registered disability	−0.081	+0.838
Unemployment	+0.558	−0.329

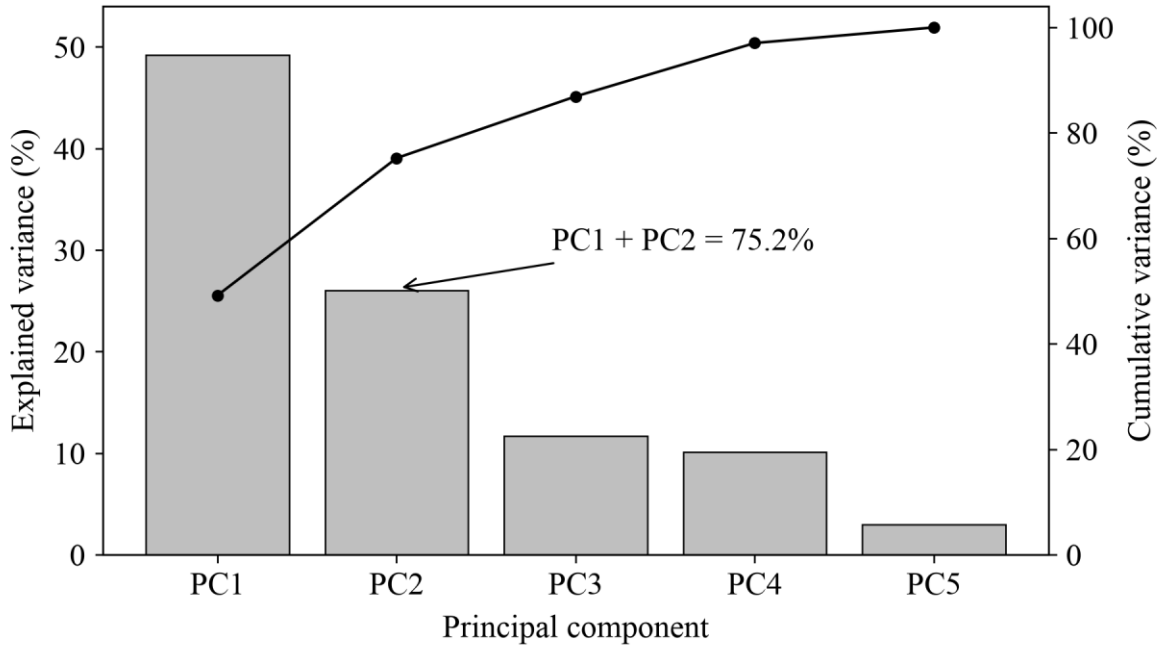


Figure 3 – Explained variance in the exposed-only PCA. PC1 and PC2 together retain 75.21% of predictor variance.

3.4. Baseline, original-indicator, and PCA-reduced mortality models

Table 5 – In-sample comparison of the three RQ2 models. Higher R^2 and adjusted R^2 are better; lower RMSE, AIC, and BIC are better.

Model	Para-meters	R^2	Adj. R^2	RMSE	AIC	BIC
Baseline: region + year	4	0.0840	0.0116	0.1023	−64.29	−57.34
Original indicators	9	0.3112	0.1443	0.0887	−66.27	−50.63
PCA-reduced: PC1 + PC2	6	0.2639	0.1617	0.0917	−69.48	−59.05

The baseline model explained 8.4% of the in-sample variation in mortality. Adding the five original indicators increased R^2 to 31.1% and lowered RMSE to 0.0887. Using PC1 and PC2 instead gave R^2=26.4% and RMSE=0.0917. The five-

indicator model therefore had the best raw fit, but the PCA model kept most of the improvement while using fewer parameters. The PCA model also had the highest adjusted R^2 and the lowest AIC and BIC.

The 2011–2021 sensitivity analysis gave the same overall pattern. The original model had R^2=0.5015 and RMSE=0.0782, while the PCA model had R^2=0.4714 and RMSE=0.0805 and still had better AIC and BIC. KMO remained weak in this shorter period (0.493), so the PCA result is still exploratory.

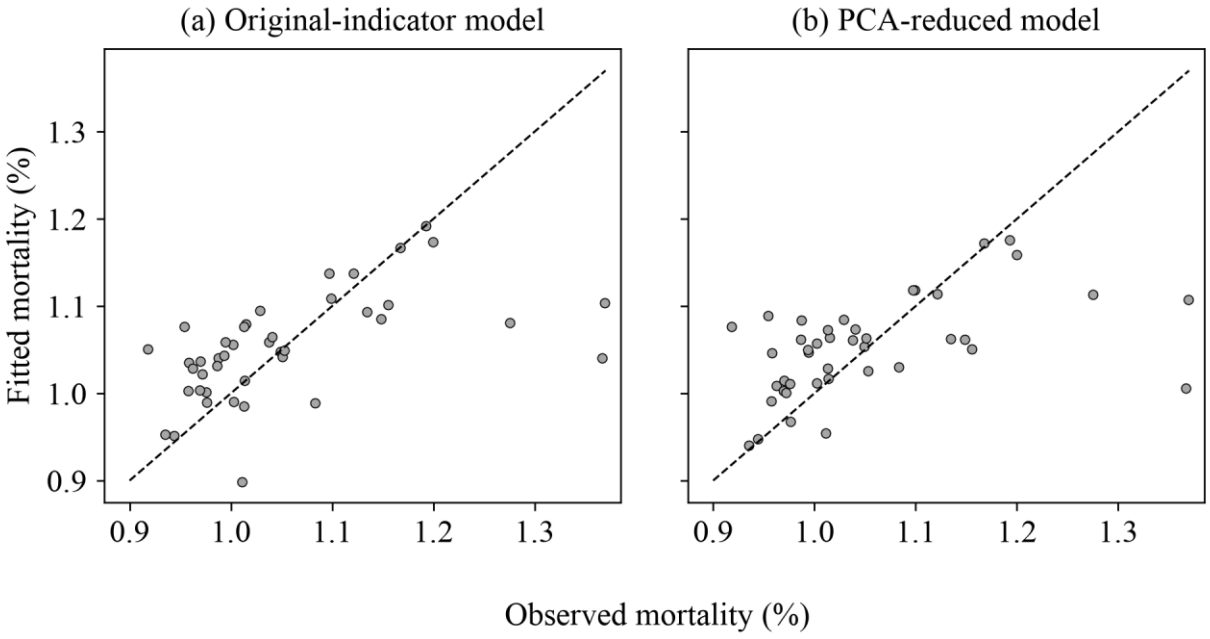


Figure 4 – Observed and fitted crude all-cause mortality using the audited mortality series. Both indicator-based models improve on the simple region-and-year baseline, but these are in-sample fits, not future forecasts. Panels (a) and (b) show the original-indicator and PCA-reduced models, respectively.

4. Discussion

4.1. Principal findings

The study answers two different questions using one checked regional dataset. RQ1 shows the broad differences between the two project-defined groups. Some indicators differ, but there are only six regions and the group labels are not based on measured dose. The pre-2022 check also shows that some results, especially disability, change when the border reform is removed.

RQ2 gives the main statistical result. PC1 and PC2 retain 75.21% of the variation in the five predictors. Both the five-indicator model and the PCA model fit observed mortality better than the simple region-and-year baseline. The five-indicator model has the best raw R^2 and RMSE, while the PCA model has better adjusted R^2, AIC, and BIC. This means PCA gives a simpler model with only a moderate loss of raw fit; it does not mean PCA predicts mortality better.

4.2. Interpretation and relationship to radiation

Some indicators have positive PCA coefficients and others have negative coefficients. For this reason, PC1 and PC2 should not be called a validated health-vulnerability index. PCA is designed to summarize variation, not to create a clinical risk score [12]. The group differences also cannot be linked directly to SNTS radiation. The study does not include individual dose, full residence history, detailed fallout data, or many possible regional confounders. The safest conclusion is that the selected regions show different regional health profiles and that the exposed-only predictor set can be simplified with limited loss of model fit.

4.3. Limitations

The study has several important limits. RQ1 includes only six independent regions and RQ2 only three, even though the regions are observed repeatedly across years. Mortality is crude rather than age-standardized. The predictors use different denominators. PCA suitability is weak overall, especially for disability. Some post-2022 regional data could not be fully rebuilt to the same borders, although a pre-2022 sensitivity check was added. The models are evaluated on the same data used to fit them, so they are not validated forecasts. HC3 helps with unequal error variance but not with serial correlation within regions. Finally, the project group labels are not based on measured radiation dose, and regional findings cannot be applied directly to individuals [13].

5. Conclusion

Across six Kazakhstan regions, the project-defined groups showed descriptive differences in several health and social indicators, but the results do not prove a radiation effect and some differences were sensitive to the 2022 border reform. Within the three exposed-classified regions, PCA reduced five indicators to two components that retained 75.21% of predictor variance. The PCA model kept much of the fit gained over the simple region-and-year baseline while using fewer predictors than the full model. The main contribution is therefore methodological: PCA can simplify this small regional dataset, but stronger boundary harmonization, more independent regions, better mortality measures, and out-of-sample validation are needed for stronger conclusions.

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Declarations

Ethics. The study uses aggregate regional statistics and no personal identifiers.

Funding. No external funding was identified.

Conflicts of interest. None declared.

Data and code availability. The audited datasets, Python analysis scripts, output tables, and figures used in this study are available in the public GitHub repository: https://github.com/Bebrapro2007/Kazakhstan-Social-Health-PCA-

Research. The repository includes a README with the project structure and instructions for reproducing the analysis.

Author contribution. Akezhan Omashev developed the dataset, analysis workflow, and manuscript.

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