WEPP configuration

WEPP was configured to mirror the controlled rainfall-simulation experiments and then to extrapolate the empirically constrained erosion processes across a broader slope-rainfall space. All simulations were run in hillslope mode, and the model structure was deliberately kept simple so that differences among scenarios reflected the restoration phase, slope, and rainfall intensity rather than undocumented parameter changes.

Hillslope geometry

WEPP configuration

WEPP was configured to mirror the controlled rainfall-simulation experiments and then to extrapolate the empirically constrained erosion processes across a broader slope–rainfall space. All simulations were run in hillslope mode, and the model structure was deliberately kept simple so that differences among scenarios reflected restoration phase, slope, and rainfall intensity rather than undocumented parameter changes.

Hillslope geometry

For calibration against the rainfall-simulation data, WEPP was set up with a hillslope length of 7 m and a width of 1.5 m, matching the experimental plots on the 20% slope. The calibrated configuration at 20% slope was then used as a reference to explore topographic effects by introducing two additional uniform slopes, one gentler (10%) and one steeper (30%), while maintaining the same hillslope length and width. Thus:

- **Calibration slope:** 20% (7 m × 1.5 m), identical to the field plots.
- **Extrapolation slopes:** 10%, 20%, and 30% (7 m × 1.5 m), representing moderate to steep hillslopes in the study region.

In all cases, slopes were specified as uniform profiles with no additional breaks so that differences in erosion response could be attributed directly to slope magnitude rather than to complex microtopography.

Climate and storm forcing.

Because a rainfall simulator generated runoff and erosion, WEPP was driven with single-storm climate inputs rather than long synthetic climate series. Each climate file consisted of a single event with constant intensity over a 30-minute duration, corresponding to the experimental and extrapolation treatments.

For the experimentally applied storms, we used:

- 50 mm h^{-1} → 25 mm total depth
- 80 mm h^{-1} → 40 mm total depth
- 120 mm h^{-1} → 60 mm total depth

To explore extreme climate forcing beyond the experimental range, we defined two additional high-intensity scenarios with the same 30-minute duration:

- 150 mm h^{-1} → 75 mm total depth
- 180 mm h^{-1} → 90 mm total depth

These single-storm climate files allow us to assess the robustness of restoration phases and planting densities under both the observed experimental conditions (50–120 mm h^{-1}) and rare but plausible extreme events (150-180 mm h^{-1}), while maintaining a direct correspondence between rainfall-simulator settings and WEPP inputs.

Soil profile

All simulations used a single silt loam soil profile representative of the Loess Plateau, with texture ≈ 10% sand, 70% silt and 20% clay (**Table S2**). Bulk density and saturated hydraulic conductivity were based on field measurements and ROSETTA pedotransfer estimates, and then refined during WEPP calibration against observed runoff. A single calibrated soil file was used for all restoration phases and slopes; thus differences among treatments were represented through vegetation/management rather than by altering the underlying soil material.

Management and restoration phases

Vegetation effects were represented through three management configurations corresponding to the restoration phases:

- **Phase I (shrubs only):** *Caragana* shrubs with relatively low total canopy and ground cover, representing a structurally simple shrub monoculture.
- **Phase II (shrubs + biocrust):** the same shrub layer as Phase I, combined with increased ground cover and surface protection to represent biological soil crusts that armour the surface and enhance roughness.
- **Phase III (shrubs + biocrust + grasses):** a multilayer system with shrub canopy, biocrust ground cover, and an understory grass layer, represented by higher total canopy and ground cover and deeper effective rooting to reflect the vertically stratified vegetation structure.

Within each phase, the shrub-density scenarios used in the extrapolations were implemented by adjusting plant and cover parameters in the management file (e.g. canopy cover and ground cover) to be consistent with the field density gradients. No additional changes in soil erodibility were made between phases, so improvements in runoff and sediment control can be attributed to the assembled vegetation structure rather than to unobserved changes in soil properties.

Full WEPP output summaries for all combinations of slope, rainfall intensity, restoration phase, and planting density used in the analysis are provided in the supplementary data file. Input parameter files matching the configuration described above are available from the corresponding author on reasonable request.

Table S1 Measured soil properties at the rainfall-simulation site on the Loess Plateau and their relevance for hydrological and erosion modelling in this study.

Parameter	Description	Value/Range	Measurement Method	Source	Notes
Soil texture (silt)	Silt fraction of surface soil (%)	70	Hydrometer method (ASTM D422-63)	Lab analysis at experimental site; used to characterise silt loam texture.	Dominant fraction in Loess Plateau soils
Soil texture (clay)	Clay fraction of surface soil (%)	20	Hydrometer method	Lab analysis, together with silt and sand,	

			(ASTM D422-63)	defines loess texture.	
Bulk density (ρ)	Dry bulk density of surface soil g/cm³	1.3	Core sampling (Blake & Hartge, 1986)	Field measurement constrains soil water storage and hydraulic parameters.	Critical for infiltration
Saturated hydraulic conductivity (Ksat)	Saturated hydraulic conductivity of surface soil mm/h	10	ROSETTA pedo transfer function (USDA-NRCS)	(Schaap, Leij et al. 1998, Centeno, Timm et al. 2020)	Derived from texture and bulk density
Initial moisture (θin)	Pre-storm soil moisture content at 0-30 cm (%)	18-35%	Gravimetric method (drying at 105°C)	Field measurement	
Nutrient concentration (*Ci*)	pre-event soil N/P concentration% % or mg/kg	N: 0.11 ± 0.1; P: 0.85 ± 0.1;	ICP-OES (Method 3050B, USEPA)	Composite soil samples (0-20 cm depth)	Critical for the nutrient transport module

Note: Soil properties were measured at 0-30 cm depth at the rainfall-simulation plots as part of this study. Values represent site-mean conditions used to characterise the silt loam soil and to inform WEPP parameterisation; the full dataset is provided in Dataset S1 (Supplementary material).

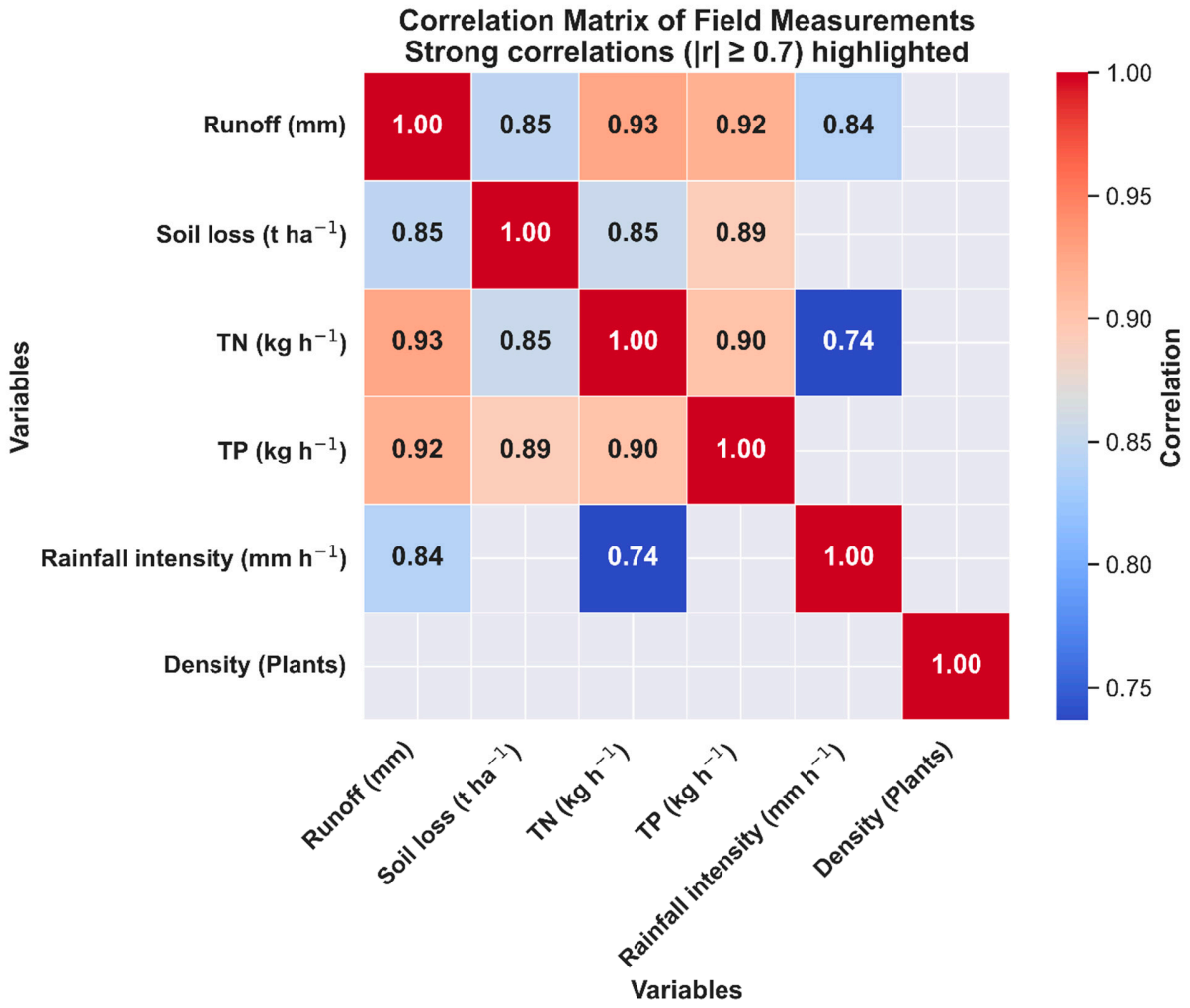


Figure S1 Correlation structure among hydrological, erosion and nutrient responses and their main drivers across all rainfall-simulation plots. The heatmap shows pairwise Pearson correlation coefficients between runoff, soil loss, total nitrogen (TN), total phosphorus (TP), rainfall intensity and shrub density. Strong relationships ($|r| \geq 0.7$) are highlighted by unmasked cells and bold correlation values, whereas weaker correlations are shaded. Correlations were estimated from field measurements under controlled rainfall simulations; 95% bootstrap confidence intervals (1,000 resamples) confirmed the robustness of the strongest associations.

Table S2 Complete optimal planting densities and performance metrics across environmental gradients and ecosystem functions

Phase	Rainfall Intensity (mm h^{-1})	Slope gradient	Runoff optimal density ha^{-1}	Runoff max reduction%	Soil loss optimal density ha^{-1}	Soil loss max reduction %	TN optimal density ha^{-1}	TN max reduction%	TP optimal density ha^{-1}	TP max reduction%	Density category
Phase I	50	10	1905	100	1905	100	1905	43.9	1905	41.6	Low
Phase I	50	20	7619	100	7619	100	7619	44.7	7619	42.4	High
Phase I	50	30	5714	100	5714	100	5714	44.7	5714	42.4	High
Phase I	80	10	9524	100	9524	100	9524	78.5	9524	76.9	Very High
Phase I	80	20	11429	81.6	11429	90.5	11429	64.1	11429	62.8	Very High
Phase I	80	30	11429	74.3	11429	94.5	11429	58.4	11429	57.2	Very High
Phase I	120	10	11429	59	11429	89.4	11429	52.3	11429	51.7	Very High
Phase I	120	20	11429	45.4	11429	74.2	11429	40.3	11429	39.8	Very High
Phase I	120	30	11429	42.1	11429	91.9	11429	37.3	11429	36.9	Very High
Phase I	150	10	11429	43.2	11429	85.4	11429	39.7	11429	39.3	Very High
Phase I	150	20	11429	33.6	11429	72.8	11429	30.8	11429	30.6	Very High
Phase I	150	30	11429	31.3	11429	90.9	11429	28.7	11429	28.5	Very High
Phase I	180	10	11429	34	11429	83	11429	31.8	11429	31.6	Very High
Phase I	180	20	11429	26.6	11429	72	11429	24.8	11429	24.7	Very High
Phase I	180	30	11429	24.8	11429	89.9	11429	23.2	11429	23	Very High
Phase II	50	10	1905	100	1905	100	1905	43.9	1905	41.6	Low
Phase II	50	20	1905	100	1905	100	1905	44.7	1905	42.4	Low
Phase II	50	30	1905	100	1905	100	1905	44.7	1905	42.4	Low
Phase II	80	10	5714	100	5714	100	5714	78.5	5714	76.9	High
Phase II	80	20	11429	93.4	11429	98.9	11429	73.4	11429	71.9	Very High
Phase II	80	30	11429	84.7	11429	97.9	11429	66.6	11429	65.2	Very High

Phase II	120	10	11429	67.8	11429	94.6	11429	60.2	11429	59.5	Very High
Phase II	120	20	11429	53.9	11429	93	11429	47.8	11429	47.3	Very High
Phase II	120	30	11429	49.9	11429	95.5	11429	44.3	11429	43.8	Very High
Phase II	150	10	11429	50	11429	91.6	11429	45.9	11429	45.5	Very High
Phase II	150	20	11429	40.2	11429	92.1	11429	36.9	11429	36.6	Very High
Phase II	150	30	11429	37.3	11429	94.6	11429	34.3	11429	34	Very High
Phase II	180	10	11429	39.5	11429	89.9	11429	36.9	11429	36.7	Very High
Phase II	180	20	11429	31.9	11429	91.6	11429	29.8	11429	29.6	Very High
Phase II	180	30	11429	29.7	11429	93.9	11429	27.7	11429	27.6	Very High
Phase III	50	10	1905	100	1905	100	1905	43.9	1905	41.6	Low
Phase III	50	20	1905	100	1905	100	1905	44.7	1905	42.4	Low
Phase III	50	30	1905	100	1905	100	1905	44.7	1905	42.4	Low
Phase III	80	10	1905	100	1905	100	1905	78.5	1905	76.9	Low
Phase III	80	20	11429	94.7	9524	99.3	11429	74.5	11429	73	Very High
Phase III	80	30	11429	84.7	9524	98.6	11429	66.6	11429	65.2	Very High
Phase III	120	10	11429	68.8	9524	96.8	11429	61	11429	60.4	Very High
Phase III	120	20	11429	54.5	9524	95.9	11429	48.4	11429	47.9	Very High
Phase III	120	30	11429	49.9	9524	97.3	11429	44.3	11429	43.8	Very High
Phase III	150	10	11429	50.7	9524	95.1	11429	46.5	11429	46.1	Very High
Phase III	150	20	11429	40.6	9524	95.4	11429	37.3	11429	37	Very High
Phase III	150	30	11429	37.3	9524	96.8	11429	34.3	11429	34	Very High
Phase III	180	10	11429	40	9524	96.3	11429	37.4	11429	37.2	Very High
Phase III	180	20	11429	32.2	9524	95.1	11429	30.1	11429	29.9	Very High
Phase III	180	30	11429	29.7	9524	96.4	11429	27.7	11429	27.6	Very High

Note: Planting densities indicate the optimal density (plants ha^{-1}) that maximizes reduction efficiency for runoff, soil loss, total nitrogen (TN), and total phosphorus (TP) relative to control

conditions. Density categories are defined as Low (<2,000), Medium (2,000-5,000), High (5,000-8,000), and Very High (>8,000) plants ha^{-1}. Restoration phases are Phase I (Caragana shrubs only), Phase II (Caragana + biocrust), and Phase III (Caragana + biocrust + grass). This dataset provides the empirical basis for the strategic framework presented in Table 2 of the main text.

References

Centeno, L. N., L. C. Timm, K. Reichardt, S. Beskow, T. L. Caldeira, L. M. de Oliveira and O. Wendroth (2020). "Identifying regionalized co-variate driving factors to assess spatial distributions of saturated soil hydraulic conductivity using multivariate and state-space analyses." Catena **191**: 104583.

Lal, R. (1994). Soil erosion research methods, CRC Press.

Schaap, M. G., F. J. Leij and M. T. Van Genuchten (1998). "Neural network analysis for hierarchical prediction of soil hydraulic properties." Soil Science Society of America Journal **62**(4): 847–855.