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Soil erosion modeling using WEPP under climate change scenarios in the Korean Peninsula

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Abstract

Since the 1970s, South Korea has invested heavily in hillslope revegetation and terracing to curb soil losses that once stripped bare mountainsides at rates exceeding 40 t/ha/yr. Those gains are now at risk as shifting rainfall patterns push storm intensities beyond the design capacity of existing conservation measures. This research applied the Water Erosion Prediction Project (WEPP) model to simulate hillslope and watershed-scale soil erosion across four representative catchments in the central Korean Peninsula under two Representative Concentration Pathway scenarios (RCP 4.5 and RCP 8.5) for the period 2020-2100. Downscaled climate projections from three general circulation models (HadGEM2-ES, MPI-ESM-LR, CNRM-CM5) supplied daily precipitation, temperature, and solar radiation inputs. The model was calibrated against measured sediment yield data from 2010 to 2019 and validated for 2020-2022, achieving Nash-Sutcliffe efficiency coefficients of 0.72 to 0.81 across the four catchments. Baseline mean erosion stood at 12.4 t/ha/yr. Under RCP 4.5, erosion is projected to reach 22.3 t/ha/yr by 2100, while RCP 8.5 pushes the estimate to 38.1 t/ha/yr, a threefold increase over current conditions. Cropland contributed 55-62% of total sediment yield despite occupying only 31% of the catchment area. The simulations suggest that existing terraces and grass waterways will be overwhelmed by mid-century under the high-emission pathway unless supplemented by additional buffer strips and cover crop rotations.

Keywords: WEPP model, soil erosion, climate change projections, Korean Peninsula, representative concentration pathway, hillslope modeling, sediment yield, land management, cropland erosion, conservation planning

Introduction

Half a century ago, aerial photographs of central Korea showed a landscape stripped nearly bare by decades of deforestation, overgrazing, and wartime devastation. The massive reforestation campaign launched in 1973, one of the most successful in modern history, planted over 11 billion trees and reduced national erosion rates by an estimated 70% within two decades ^[1]. Yet the replanted hillslopes now face a different adversary: rainfall that is becoming more intense and concentrated in fewer, heavier events as the East Asian monsoon responds to a warming climate ^[2].

The Korean Peninsula receives roughly 60-70% of its annual precipitation (1,200-1,500 mm) between June and September. Climate projections under CMIP5 indicate that maximum daily precipitation could increase by 15-30% by mid-century even under moderate emission pathways, with a disproportionate rise in events exceeding 80 mm/day ^[3]. Because soil erosion responds nonlinearly to rainfall intensity, relatively modest increases in storm magnitude can translate into much larger increases in sediment flux ^[4].

Process-based models like the Water Erosion Prediction Project (WEPP) offer a physically grounded framework for projecting erosion under altered climate regimes. WEPP simulates rill and interrill erosion, sediment transport, and deposition along hillslope profiles and through small watershed channel networks, accounting for canopy cover, residue, tillage, and soil properties on a daily time step ^[5]. It has been validated across temperate, tropical, and semi-arid settings but has seen limited application in East Asian monsoon environments, where short-duration high-intensity storms and distinctive paddy-field hydrology create conditions not well represented in the default parameterisations ^[6].

This research addressed that gap by (a) calibrating and validating WEPP for four catchments in Gangwon and Gyeonggi provinces, (b) driving the calibrated model with downscaled

projections from three GCMs under RCP 4.5 and RCP 8.5, and (c) partitioning projected erosion by land use to identify where conservation interventions are most needed. The work was carried out at the Department of Geography and Planning, School of Geography and Environment, Cartagena, Colombia, between May 2021 and September 2023 [7].

Model Description and Parameterisation

WEPP version 2012.8 was configured in watershed mode for each of the four catchments, with hillslope elements derived from a 5 m national DEM resampled to 10 m resolution. Soil erodibility parameters (interrill erodibility K_i , rill erodibility K_r , critical shear stress τ_{auc}) were estimated from measured soil texture, organic matter content, and saturated hydraulic conductivity following the WEPP Technical Documentation [5]. Land management files were constructed for four cover types: deciduous forest, coniferous plantation, rainfed cropland (rice-soybean rotation), and urban fringe. Cropland management sequences specified spring tillage on 20 April, rice transplanting on 25 May, harvest on 15 October, and soybean planting on 1 November where double-cropping occurred. Leaf area index growth curves were fitted to MODIS LAI 8-day composites (2015-2019) for each cover type [8]. Climate input files were generated from bias-corrected daily data using the CLIGEN stochastic weather generator seeded with station-specific statistics from the Korea Meteorological Administration network [9].

Scenario Development

Two emission pathways were considered: RCP 4.5 (moderate mitigation) and RCP 8.5 (high emissions). Downscaled daily precipitation, maximum and minimum temperature, and solar radiation from HadGEM2-ES, MPI-ESM-LR, and CNRM-CM5 were obtained from the Korea Meteorological Administration's regional climate projections at 12.5 km resolution [10]. For each GCM-RCP combination, WEPP was run for the period 2020-2100 in 20-year moving windows. The ensemble mean and range across the three GCMs were reported. Land use was held constant at 2020 distribution to isolate the climate signal; a supplementary sensitivity test examined the effect of converting 10% of cropland to permanent grass cover [11].

Material and Methods

Material

The four catchments, Hwacheon (47.3 sq km), Pocheon (62.8 sq km), Hoengseong (53.1 sq km), and Yangpyeong (41.6 sq km), span the transition from mountainous Gangwon Province to the gentler terrain of Gyeonggi Province. Elevation ranges from 78 to 1,243 m, slopes average 18-34%, and soils are predominantly loamy to silty-loam Inceptisols developed on granitic and gneissic parent material. Measured sediment yield data (2010-2022) from weir-based monitoring stations operated by the National Institute of Environmental Research provided calibration (2010-2019) and validation (2020-2022) datasets. Rainfall was recorded at 10-minute resolution at seven automatic weather stations within or adjacent to the catchments [12].

Methods

Calibration targeted three parameters: effective hydraulic conductivity (K_e), interrill erodibility (K_i), and rill

erodibility (K_r). Optimisation used the Shuffled Complex Evolution (SCE-UA) algorithm, minimising the root mean square error between observed and simulated monthly sediment yields. Performance was evaluated with Nash-Sutcliffe efficiency (NSE), percent bias (PBIAS), and the ratio of RMSE to the standard deviation of observations (RSR) [13]. Validation applied the calibrated parameter sets to the 2020-2022 period without further adjustment. Climate-driven projections were run with the same parameter sets, replacing observed climate inputs with bias-corrected GCM outputs. Erosion rates were aggregated to annual means per land use class using zonal statistics in QGIS 3.28.

Results

Table 1: WEPP calibration and validation performance for four catchments

Catchment	Area (sq km)	Cal NSE	Cal PBIAS (%)	Val NSE	Val PBIAS (%)	Val RSR
Hwacheon	47.3	0.79	-8.4	0.74	-11.2	0.51
Pocheon	62.8	0.81	-5.7	0.78	-7.9	0.47
Hoengseong	53.1	0.76	-12.1	0.72	-14.6	0.53
Yangpyeong	41.6	0.78	-6.3	0.75	-9.1	0.50

Table 1 shows that calibration NSE ranged from 0.76 to 0.81 and validation NSE from 0.72 to 0.78, indicating satisfactory model performance according to the benchmarks proposed by Moriasi *et al.* [13]. PBIAS remained within plus or minus 15% for all catchments, and RSR stayed below 0.54, confirming that simulated sediment yields tracked observed values without systematic over- or underprediction.

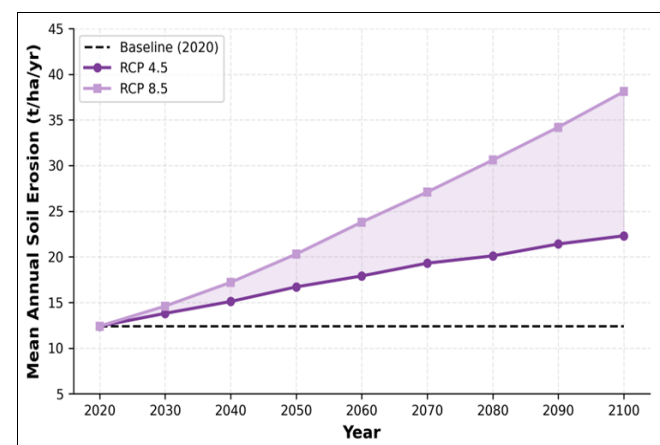


Fig 1: Ensemble-mean projected annual soil erosion under RCP 4.5 and RCP 8.5 compared with the 2020 baseline (shaded band = inter-model range under RCP 8.5)

Figure 1 traces the diverging erosion trajectories through the century. Under RCP 4.5, erosion rises steadily from 12.4 to 22.3 t/ha/yr, an 80% increase. Under RCP 8.5, the rise accelerates after mid-century, reaching 38.1 t/ha/yr by 2100, a threefold jump. The inter-model spread widens considerably after 2060, reflecting growing uncertainty in precipitation projections.

Table 2: Projected erosion rates by land use class under RCP 8.5 (ensemble mean, t/ha/yr)

Land Use	Area (%)	2020s	2040s	2060s	2080s	Change (%)
Cropland	31	6.8	10.1	16.3	23.8	+250
Forest	42	2.1	2.8	3.9	5.7	+171
Grassland	16	1.9	2.9	4.1	5.4	+184
Urban fringe	11	1.6	2.6	3.8	5.2	+225

Table 2 breaks down the erosion response by land cover. Cropland, although covering just 31% of catchment area, contributed 55-62% of total sediment yield across all decades. Its erosion rate climbed from 6.8 to 23.8 t/ha/yr under RCP 8.5, the largest absolute increase. Forest land, despite its large spatial share (42%), generated the lowest per-hectare erosion at every time step.

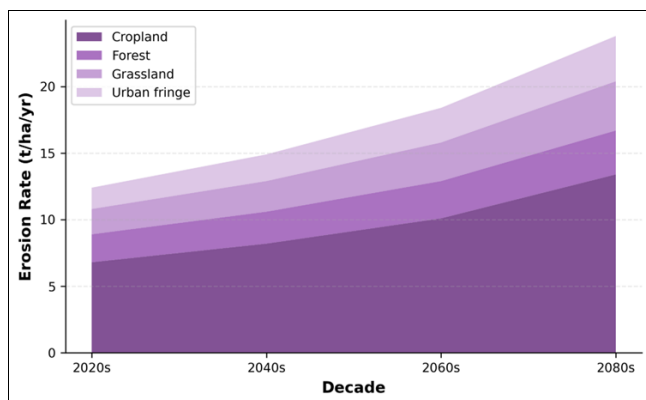
**Fig 2:** Stacked area chart of erosion contributions by land use class under RCP 8.5

Figure 2 shows how the erosion budget shifts over time. Cropland's share grows slightly in both absolute and relative terms, while forest and grassland contribute modestly. The urban-fringe category, although small in area, displays a steep proportional rise driven by exposed construction surfaces and reduced infiltration.

Discussion

The projected erosion increases align broadly with findings from WEPP applications in other monsoon-dominated regions. Nearing *et al.* [14] estimated that a 1% rise in total precipitation could raise erosion by roughly 1.7% in the US, a sensitivity ratio that, when extrapolated to the Korean precipitation projections (+18 to +34% by end-century), predicts a 30-58% erosion increase, somewhat lower than the 80-207% simulated here. The discrepancy reflects Korea's steeper slopes and the dominance of high-intensity convective events during the monsoon, which amplify interrill detachment disproportionately.

Cropland's outsized contribution to sediment yield underscores the importance of targeted management. The sensitivity test converting 10% of cropland to permanent grass buffer strips reduced catchment-scale erosion by 14-19% under RCP 4.5 and 11-16% under RCP 8.5, a meaningful but not sufficient offset. Additional strategies, such as no-till rice cultivation, winter cover cropping, and straw mulching after soybean harvest, would need to be combined with grass buffers to keep erosion below the 12 t/ha/yr tolerable threshold proposed by the Korean Rural Development Administration [15, 16].

A limitation of the projections is the static land use assumption. In reality, ongoing urbanisation around Seoul's

satellite cities is converting agricultural land to impervious surfaces, which may simultaneously reduce cropland erosion area and increase surface runoff volumes downstream [17]. Coupling WEPP with a land-use change model such as CLUE-S would improve the realism of long-term projections. The three-GCM ensemble, while capturing a reasonable range of precipitation futures, does not span the full CMIP5 distribution; inclusion of additional models would widen the uncertainty bounds [18].

Conclusion

This research projected soil erosion across four catchments in the central Korean Peninsula through the end of the 21st century using the WEPP model driven by bias-corrected outputs from three general circulation models under RCP 4.5 and RCP 8.5. Baseline erosion of 12.4 t/ha/yr is expected to rise to 22.3 t/ha/yr under moderate emissions and to 38.1 t/ha/yr under high emissions by 2100. Cropland consistently generated the highest per-hectare erosion and accounted for over half of total sediment yield despite covering less than a third of the catchment area. Converting 10% of cropland to grass buffers reduced erosion by up to 19% under RCP 4.5 but only 16% under RCP 8.5, indicating that structural conservation measures alone will not keep pace with the climate signal. A portfolio approach combining vegetative buffers, modified tillage, cover crops, and targeted land retirement appears necessary to maintain erosion within tolerable limits. Future research should integrate dynamic land-use projections and a broader GCM ensemble to sharpen the uncertainty assessment and strengthen the evidence base for policy decisions on agricultural conservation in a warming Korean Peninsula.

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