Landslide-Induced Impacts on Amphibian Habitats under Climate Change Scenarios -Republic of Korea-

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Introduction

Climate change has markedly intensified precipitation extremes worldwide, and the Republic of Korea has experienced a similar shift from moderate rainfall to episodic, high-intensity downpours. Such events exacerbate soil erosion and debris flows across mountainous and peri-urban landscapes, transporting fine sediments into stream networks, degrading water quality, and promoting eutrophication that disrupts aquatic ecosystem function. Moreover, the collapse of riparian buffer zones once critical interfaces between forests and wetlands has deprived habitat-specialist amphibians of essential refugia, leading to population fragmentation and increased extinction risk. Although the independent modeling of landslide susceptibility and amphibian habitat suitability is well established, integrated assessments of how climate-driven landslide dynamics impact amphibian distributions remain scarce. To address this gap, the present study develops a nationwide landslide susceptibility map for 2010-2019, evaluates the spatial concurrence of high-risk landslide zones with the distributions of 12 amphibian species observed from 2006 to 2018, and projects future shifts in both landslide hazard and amphibian habitat suitability under SSP2 and SSP5 climate scenarios in order to quantify emerging threat levels to amphibian populations.

Methodology

This study covers the entire Republic of Korea (excluding offshore islands) and uses historical landslide records (2010-2019) and amphibian occurrence data (2006-2018;Table 1), along with SSP2 and SSP5 climate projections for the mid-century (2041-2070) and late-century (2071-2100) periods. First, we conducted PCA on 2,995 landslide locations and corresponding terrain, vegetation, soil, and climate predictors (Table 2) at a 1 km resolution, retaining only variables contributing to the first two components (≥80% of total variance) and removing any with VIF≥10. Nine machine-learning algorithms (ANN, CTA, FDA, GAM, GBM, MARS, MAXENT, SRE, XGBoost) were each trained on these predictors to produce individual susceptibility maps. Models achieving ROC AUC≥ 0.7 were then combined via an AUC-weighted ensemble to generate a final landslide susceptibility map, with the top 20% of grid squares designated as high-risk areas. We next applied the same pipeline to model potential distributions of 13 amphibian species using the habitat variables in Table 3, converting ensemble outputs into binary suitability maps using a defined threshold. Finally, updated landslide and habitat maps under each climate scenario were overlaid in GIS, and the total area of overlapping grid squares was summed to quantify species-specific habitat loss and assess relative vulnerability under future conditions.

Table 1. Amphibian Species and Occurrence Points

Scientific Name	Occurrence Points	Remarks
Bombina orientalis	1,407	-
Bufo stejnegeri	254	-
Hynobius leechii	4,821	-
Hynobius yangi	28	Korean endemic, Endangered II
Kaloula borealis	173	Endangered II
Karsenia koreana	31	Korean endemic
Lithobates catesbeianus	3,210	Invasive alien species
Onychodactylus fischeri	312	-
Rana coreana	2,202	Korean endemic
Rana dybowskii	5,327	-
Rana huanrenensis	1,436	-
Rana nigromaculata	8,971	-
Rana rugosa	2,671	-

Table 2. Landslide Susceptibility Variables

Category	variables	Data Source
Topography	slope	National Geographic Information Service (2010–2019)
	aspect	
	DEM	
	elevation	
	plan curvature	
	profile curvature	
	SPI	
	TWI	
	geology	Korea Geological Research Institute (2023)
Soil	soil depth	Korea Forest Service (2019)
	soil type	
Vegetation	forest type	
	diameter class	
	age class	
Climate	summer rainfall	Korea Meteorological Administration (2010–2019)
	daily maximum rainfall	

Table 3. Amphibian Habitat Variables

Category	variables		Data Source
Climate	bio1(Annual Mean Temperature)	bio2(Mean Diurnal Range)	Korea Meteorological Administration (2010–2019)
	bio3(Isothermality)	bio4(Temperature Seasonality)	
	bio5(Max Temperature Warmest Month)	bio (Min Temperature Coldest Month)	
	bio7(Annual Temperature Range)	bio8(Mean Temperature Wettest Quarter)	
	bio9(Mean Temperature Driest Quarter)	bio10(Mean Temperature Warmest Quarter)	
	bio12(Annual Precipitation)	bio13(Precipitation Wettest Month)	
	bio14(Precipitation Driest Month)	bio17(Precipitation Driest Quarter)	
Land-use distance	Broadleaf Forest	Coastal Wetland	National Geographic Information Service (2018)
	Coniferous Forest	Agricultural Field	
	Inland Wetland	Mixed Forest	
	Paddy Field	-	

Results & Discussion

We evaluated landslide susceptibility and potential distributions for 13 amphibian species across five scenarios: historical (2010s; landslides 2010-2019, amphibians 2006-2018), SSP2 mid-century (2041-2070), SSP2 late-century (2071-2100), SSP5 mid-century, and SSP5 late-century. Three species (Kaloula borealis, Karsenia koreana, Lithobates catesbeianus) were excluded due to low model performance (ROC AUC <0.7).Within landslide susceptibility areas (LSA), four species Bombina orientalis, Bufo stejnegeri, Hynobius leechii, Hynobius yangi lost over 90% of their habitat area (HA in LSA) relative to the 2010s baseline under all future scenarios. In contrast, three species Rana coreana, Rana dybowskii, and Rana nigromaculata showed HA in LSA increases of 100-300% or maintained their habitat extent.Species experiencing drastic habitat loss suffered from overall climatic niche contraction, leaving little suitable area even before accounting for landslide risk. Conversely, species with stable or expanding HA in LSA exhibited smaller shifts in climate suitability, allowing them to retain or gain potential habitat within LSA despite increased landslide hazards. These divergent responses highlight that climate-driven landslide impacts will vary markedly among Korean amphibians, underscoring the need for species-specific conservation strategies that prioritize highly vulnerable taxa while leveraging the resilience of more adaptable species.

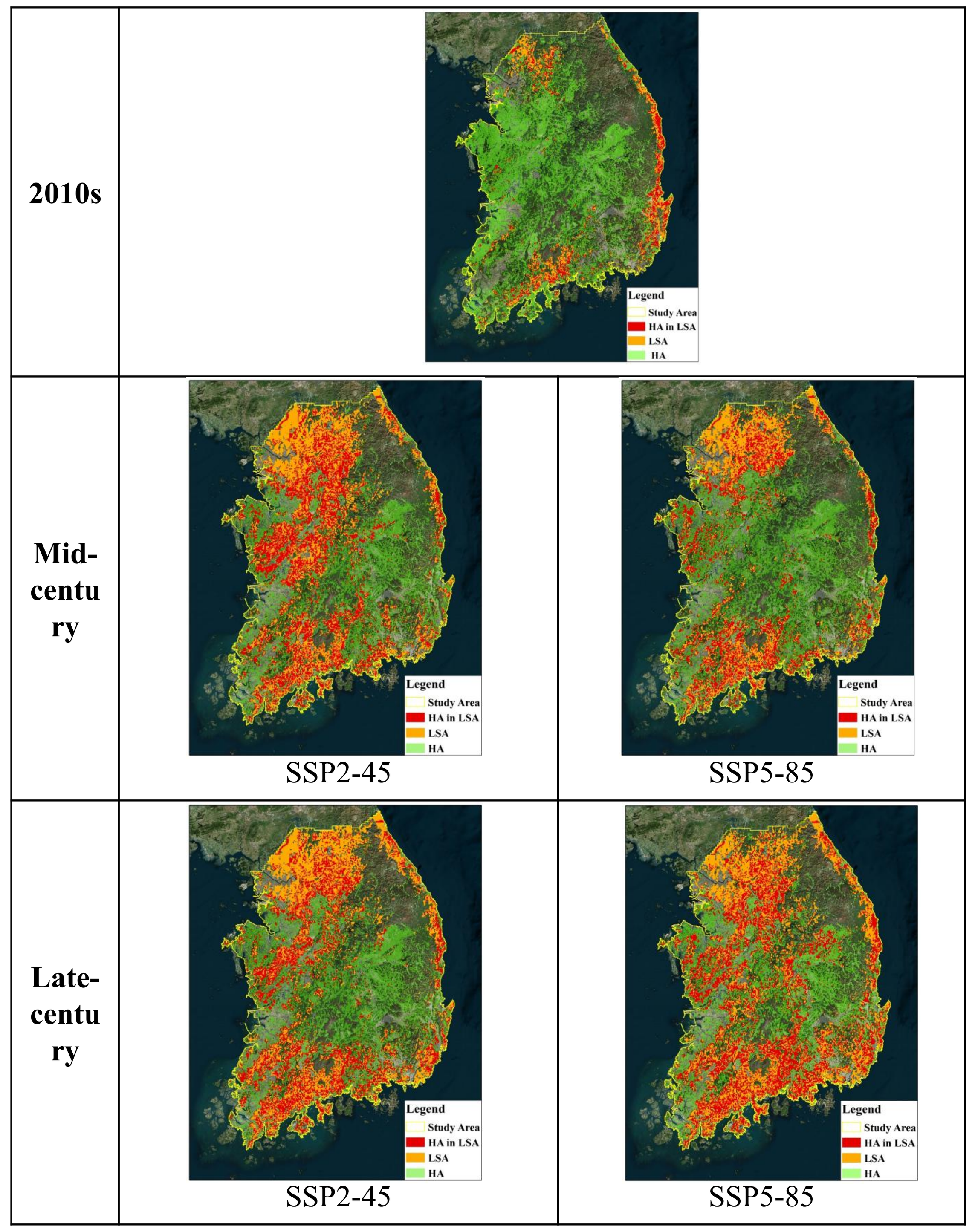

Figure 1. Potential Habitat Changes of the Amphibian (Rana coreana) within Landslide-Prone Areas

Table 4. Changes in Potential Amphibian Habitat Area within Landslide Susceptibility Regions under SSP Climate Scenarios

Species	2010S		SSP2-Mid-century (km²)			SSP2-Late-century (km²)			SSP5-Mid-century (km²)			SSP5-Late-century(km²)		
	HA	HA in LSA	HA	HA in LSA	Change(%)	HA	HA in LSA	Change(%)	HA	HA in LSA	Change(%)	HA	HA in LSA	Change(%)
Bombina orientalis	38,651	1,638	227	7	-99.57	121	3	-99.82	121	2	-99.88	0	0	-100.00
Bufo stejnegeri	14,856	3,395	966	33	-99.03	450	12	-99.65	450	6	-99.82	64	3	-99.91
Hynobius leechii	45,686	5,250	2,571	431	-91.79	1,544	149	-97.16	1,544	102	-98.06	327	38	-99.28
Hynobius yangi	9,466	2,029	1,269	90	-95.56	1,269	9	-99.56	1,269	85	-95.81	1,269	108	-94.68
Rana coreana	**35,358**	**3,395**	**35,868**	**14,66**	**331.96**	**35,866**	**13,113**	**286.24**	**35,866**	**9,693**	**185.51**	**35,865**	**16,847**	**396.23**
Rana dybowskii	52,223	5,250	30,122	11,731	123.45	24,983	8,450	60.95	24,983	5,890	12.19	5,804	2,472	-52.91
Rana huanrenensis	23,904	2,029	8,670	826	-59.29	5,827	459	-77.38	5,827	211	-89.60	1,100	92	-95.47
Rana nigromaculata	46,445	4,504	51,296	19,147	325.11	51,376	17,379	285.86	51,376	12,731	182.66	51,879	22,106	390.81
Rana rugosa	41,404	4,168	1,029	106	-97.46	954	98	-97.65	954	83	-98.01	894	100	-97.60

*** (HA = habitat area; HA in LSA = habitat area within landslide susceptibility areas)**

Conclusion

We combined national-scale landslide susceptibility and amphibian habitat models to quantify habitat loss threat levels under past and future climate scenarios. Our ensemble-based approach offers actionable insights for landslide risk management and amphibian conservation.

This study assessed the impacts of landslides on amphibian habitats using a simple spatial overlay, but future research should employ more advanced impact analyses such as dynamic connectivity modeling and species movement simulations to capture complex ecological responses.

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