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CLIMATE MEETS POLLUTION: DUAL-MODEL MAPPING OF LIMESTONE SURFACE RECESSION ACROSS BIOGEOGRAPHICAL EUROPE

STECCI

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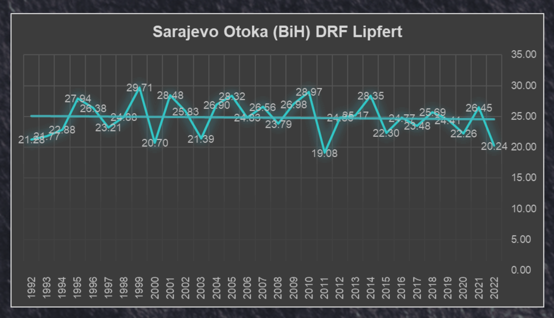
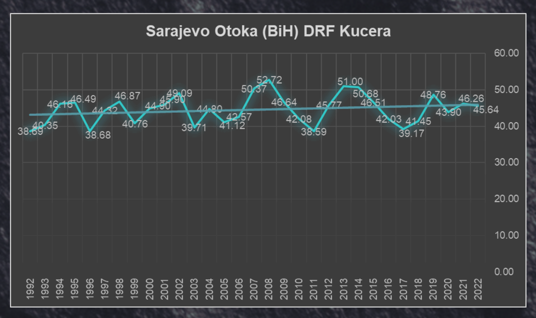
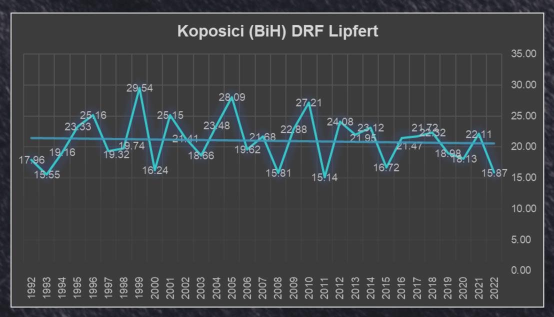
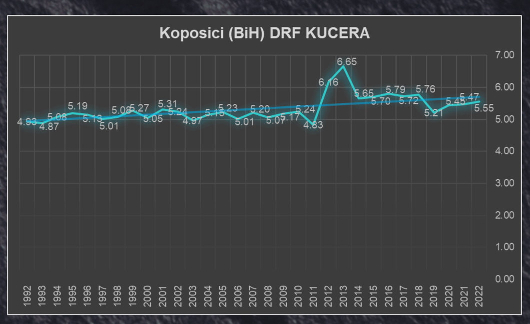
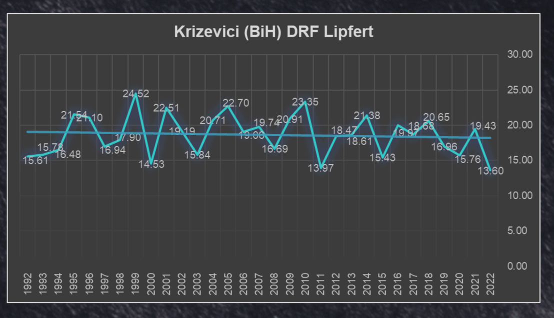
Increasingly exposed to the combined impacts of climate change and air pollution, limestone monuments are undergoing accelerated material degradation. This study applies a dual-model approach to quantify limestone surface recession at 15 heritage sites between 1992 and 2023, using two dose–response functions: Lipfert (focused on precipitation-driven acid dissolution) and Kucera (multi-pollutant based). Sites were selected to represent a broad spectrum of climatic conditions, pollutant exposure levels, and biogeographical zones across Europe, including continental, alpine, and Mediterranean regions, both urban and rural contexts. These include Sarajevo, Križevići, Kopošići, Blidinje, Ravanjska Vrata (BiH), Mramorje (RS), Split and Velika Cista (CRO), Žugića Bare (MNE), Mdina Rabat (MT), Hundskirche (AT), Unsleben and Kleinbardorf Jewish Cemeteries (DE), and Caen (FR). Harmonized environmental datasets (SO_2, NO_x, PM_{10}, temperature, and precipitation) reveal divergent model sensitivities: Lipfert estimates are higher in humid, high-rainfall zones (Žugića Bare), while Kucera better reflects pollutant-driven deterioration in urban contexts (Sarajevo, Mdina Rabat). These findings highlight site-specific degradation dynamics shaped by climate and air quality interactions. This evidence-based approach supports integrated risk mapping and the development of adaptive conservation policies at regional and European levels.

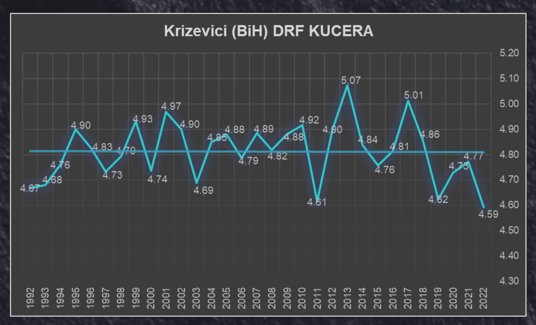


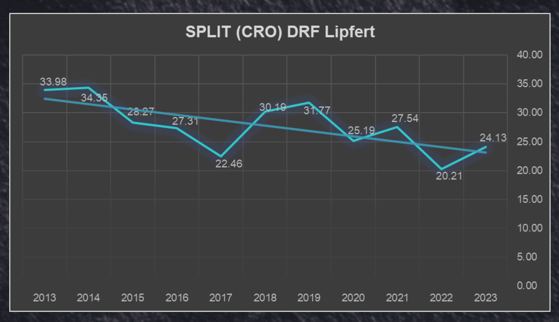


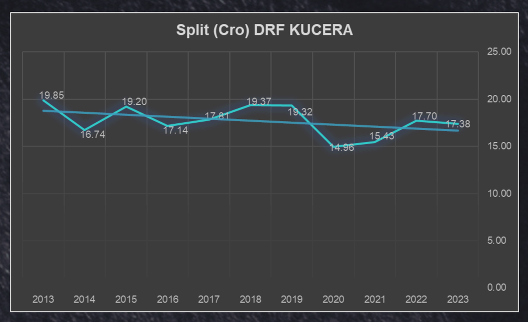


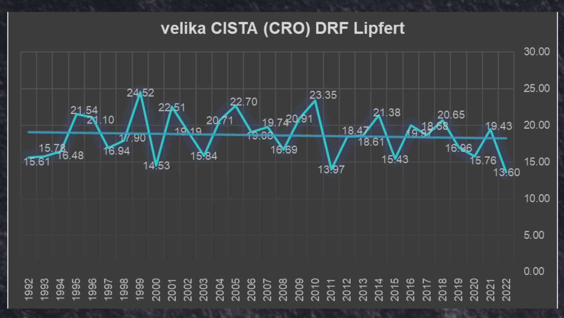


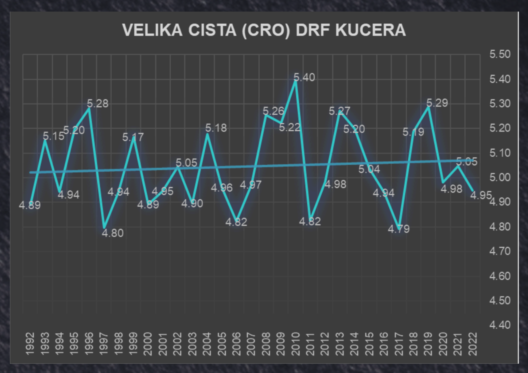


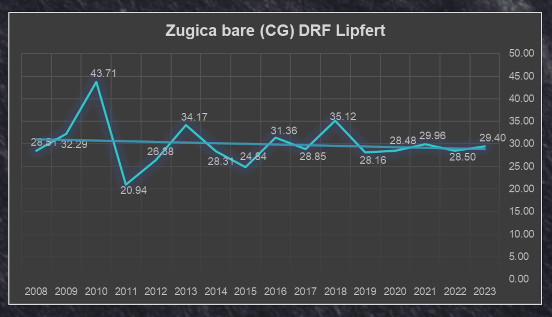


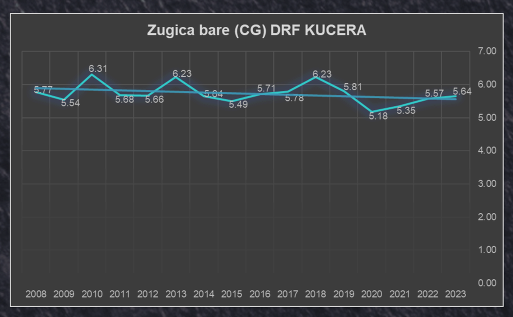


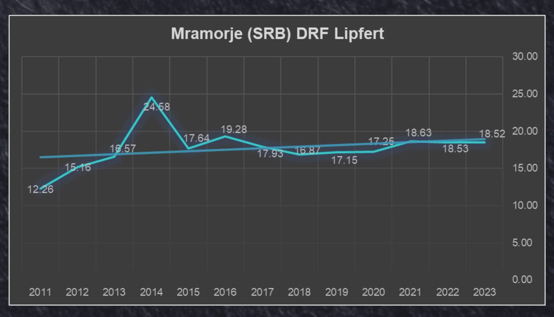


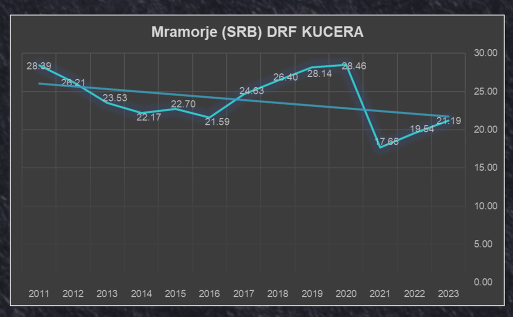












Lipfert, 1989), used to determine the erosion index of carbonate materials in the Risk Map of Cultural Heritage at national level in Italy (Ministero per i Beni e le Attività Culturali, 1996).

Lipfert (1989)

$$L = 18.8 \cdot R + 0.016 \cdot [H+] \cdot R + 0.18\,(VdS\,[SO2] + VdN\,[HNO3])$$

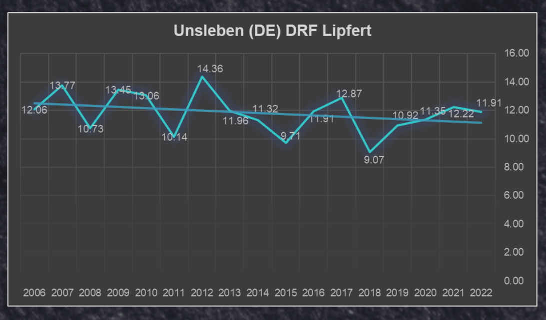
L = surface recession per year (μm year− 1); 18.8 =intercept term based on the solubility of CaCO3 in equilibrium with 330 ppm CO2 (μm m− 1); R =precipitation (m year− 1); 0.016 =constant valid for precipitation pH in the range 3–5; [H+] = hydrogen ion concentration (μmol l− 1) evaluated from rain yearly pH; 0.18 =conversion factor from (cm s− 1) (μg m− 3) to μm; VdS = deposition velocity of SO2 (cm s− 1); [SO2] = SO2 concentration (μg m− 3); VdN = deposition velocity of HNO3 (cm s− 1) and [HNO3] = HNO3 concentration (μg m− 3).

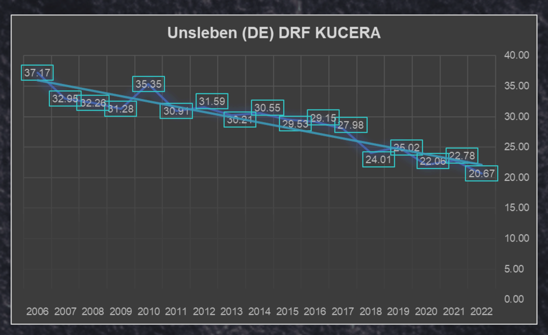
Kucera et al. (2007)

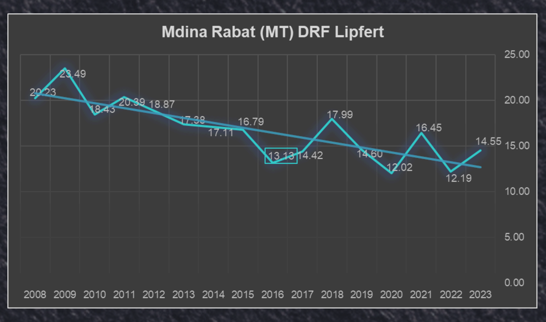
$$R = 3.95 + 0.0059[SO2]RH60 + 0.054Rain\,[H+] + 0.078\,[HNO3]\,RH60 + 0.0258\,PM10$$

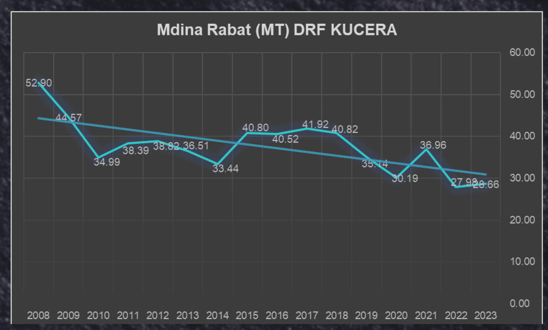
R = surface recession per year (μm/year− 1), [SO2] = SO2 concentration (μm/m− 3), RH60 = is the measured relative humidity when RH N 60 otherwise 0, Rain = amount of rainfall (mm) and [H+] = H+ concentration (0.0006–0.13 mg l− 1), [HNO3] = HNO3 concentration (μm/m− 3), PM10 = particulate matter concentration (μg/m− 3).

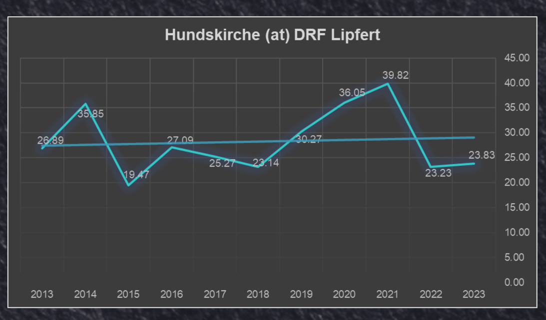
	STECCI LOCATIONS	Kucera (μm/year)	Lipfert (μm/year)	Kucera (μm/year)	Lipfert (μm/year)	MAIN FACTORS
Urban, High Pollution (SO_2 > 10 μg/m³, PM_{10} > 50 μg/m³)	Sarajevo (BIH)	44.58	23.26	40-60+ (can exceed 100 in extreme cases)	N/A (Lipfert model does not apply in SO_2-rich areas)	Acid rain, SO_2 gas dissolution, particulate deposition
Moderate Pollution (SO_2 <10 μg/m³, PM_{10} >20 μg/m³)	Mdina Rabat (MT)	37.66	16.75	20-40	N/A	Particulate deposition
	Unsleben (DE)	29.03	11.81			
	Mramorje (RS)	23.89	17.72			
Moderate Pollution, Low Pollution (SO_2 < 5 μg/m³, PM_{10} < 20 μg/m³)	Caen (FR)	18.11	12.07	5-20 (SO_2 still contributes, but reduced impact)	considering	Low SO_2 contribution, some acid rain, traffic pollutants
	Split (CRO)	17.72	27.76			
Rural, Low Rainfall (<500 mm/year, arid/semi-arid)	N/A	N/A	N/A	1-5	1-3	Natural weathering dominates, slow dissolution
Rural, Moderate Rain (500-1000 mm/year)	Kopošići (BIH)	5.33	21.02	2-7	5-10	Low air pollution, but precipitation increases limestone dissolution
	Križevići (BIH)	4.81	18.65			
	Velika Cista (CRO)	5.05	25.77			
Mountainous, High Rainfall (1000-2000 mm/year)	Hundskirche (AT)	19.72	28.26	20-30	10-30	Rainwater dissolution accelerates loss even in clean air
Remote, Very High Rainfall (2000 m/year, tropical/marine)	Žugića Bare (ME)	5.72	29.94	5-15	15-30+	Pure rainfall-driven dissolution

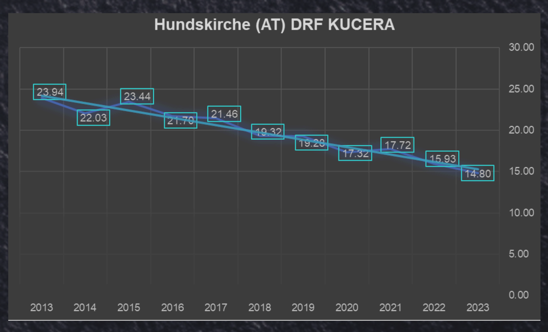


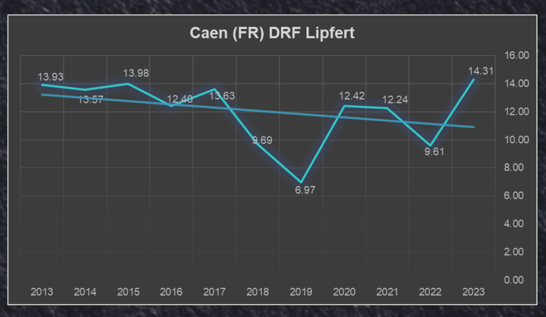


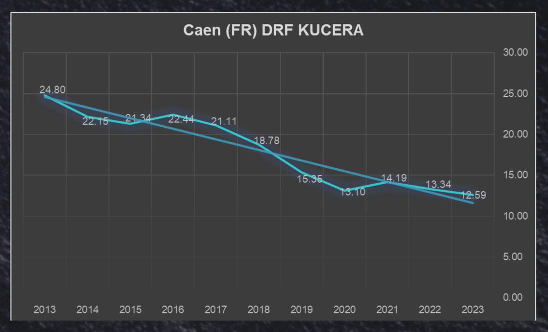












CONCLUSION Lipfert & Kucera DRF

The core part of this research presents the review of limestone dissolution rates (μm/year) under multiple environmental settings of STECCI sites, according to two DRF models, under the effect of pollution levels, rainfall, and geographical aspects. The findings show how, with considerable differences depending on location, air quality and precipitation form the weathering process of limestone.

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DISCLAIMER

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