Accounting for environmental change and uncertainties in landslide susceptibility modeling: case study of the eastern Alpine forelands in Austria

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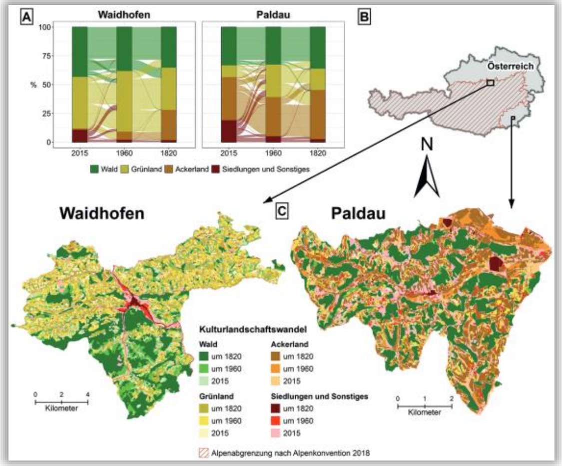
About me

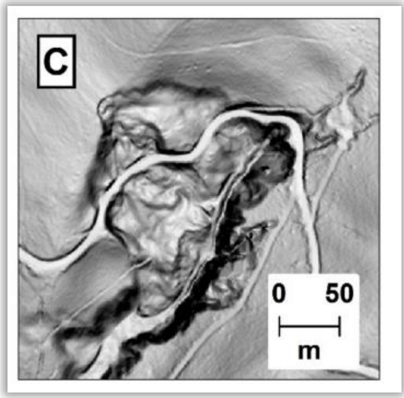
- Bachelor of Science in **Geography** (2010 – 2014), Bonn
- Master of Science in **Geoinformatics** (2014 – 2017), Jena
- Since then Academic Qualification Doctoral candidate, Jena



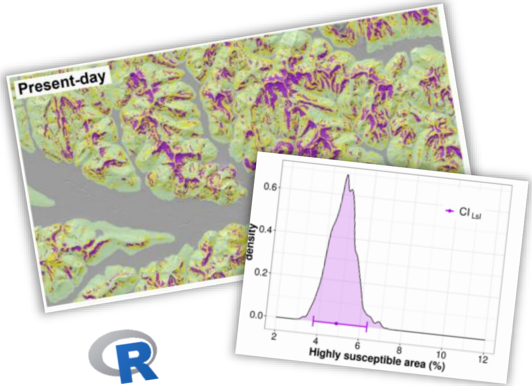
(KNEVELS et al., 2021)

Key research areas:

- Landslide science
- Cultural landscape change



(KNEVELS et al., 2019)



(KNEVELS et al., 2023)

Content

1 Motivation & Research Objectives

1 Motivation

- Landslides are natural events occurring worldwide
  - major geomorphic process
  - driver for erosion and sediment yield

(HOVIUS et al., 1997)

- **But,** when threatens infrastructure or human lives, it becomes a natural hazard

- Between 1998 and 2017, 4.8 million people were affected by landslides, causing more than 55,997 deaths and over 5.28 billion US$ total damages

(WALLEMACQ et al., 2018)

- Landslide-associated casualties are likely to increase due to climate and land-use/land cover (LULC) change

(GARIANO & GUZZETTI, 2022)

Landslide in the Feldbach Region
Foto: Alois Urbanitsch, Federal State of Styria

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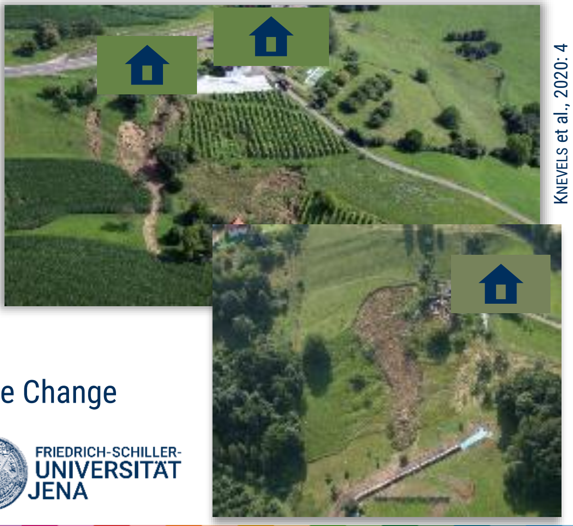
1 Motivation

- Austrian Alps and their forelands show high proneness to landslides – main natural hazard
  - conditioned by local geomorphology, geology, and LULC (LIMA et al., 2021)
  - mainly triggered by prolonged heavy rainfall and rapid snowmelt
  - hazardous interplay of mountainous regions and relatively dense population

(SCHWEIGL & HERVÁS, 2009; FUCHS et al., 2022)

- June 2009 and September 2014 heavy rainfall in the Styrian Basin
  - > 100 mm in 24 h, 50-year return period
  - > 3000 landslides, > 13.4 Mio. € damages
  - state of emergency was declared



KNEVELS et al., 2020: 4

HORNICH & ADELWÖHRER, 2010: 460

- **EASICLIM** - **E**astern **A**lpine **S**lope **I**nstabilities under **Clim**ate Change

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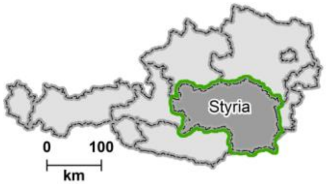
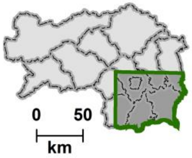
1 Research Objectives



Overarching aim is to account for environmental changes in landslide susceptibility modeling, to improve the understanding of the effects of these changes on landslide susceptibility, and to examine the uncertainties in the modeling framework for the eastern Alpine forelands in Austria as case study



Specifically we ask:

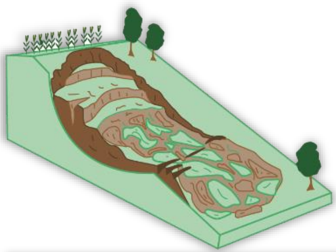
- **Q1:** What role do rainfall, soil moisture and LULC have in explaining landslides occurring during extreme weather events in the Styrian basin?
- **Q2:** What effects do LULC and climate changes have on storylines of landslide susceptibility?
- **Q3:** How uncertain are landslide susceptibility estimates emerging from an integrated modeling framework accounting for environmental change?

2 Landslide Susceptibility Modeling in the Styrian Basin

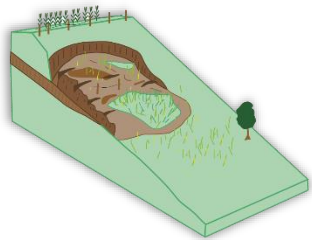
2 What is a landslide?

- A **landslide** is a downslope movement of a mass of rock, debris or earth material (*mass movement, slope failure*) (CRUDEN & VARNES, 1996)
- **Landslide susceptibility** denotes the likelihood of an area to have a landslide occurrence, given a set of local terrain and environmental conditions (BRABB, 1984)

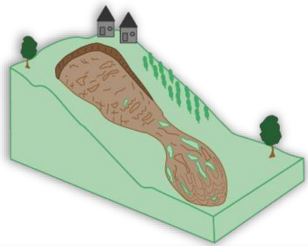
Rotational slide



Translational slide

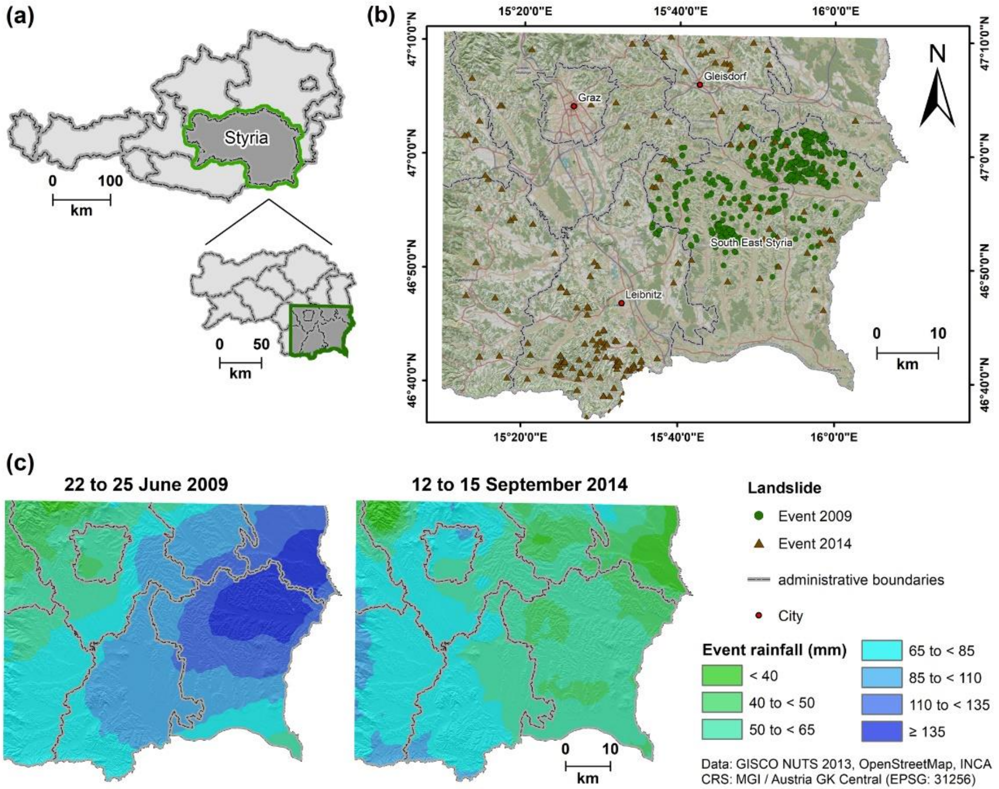


Complex slide flow



Fotos: Institut für Militärisches Geowesen
Orthophoto: Federal State of Styria

2 Overview of Study Area



(KNEVELS et al., 2023: 208)

2 Data and Methods

- environmental change
(4 climate models, 4 climate scenarios, 1 LULC scenario)

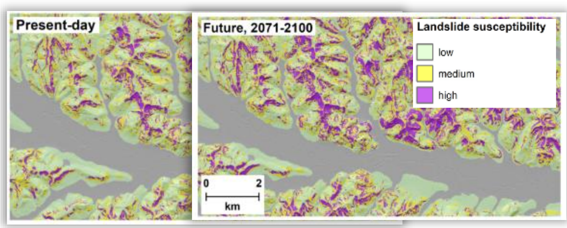
Land surface variables	Geology	Land use/land cover	Hydrometeo-rological variables	Gaussian process
LiDAR-HRDTM based slope angle slope aspect curvature normalized height convergence index flow accumulation Topographic Wetness Index SAGA Wetness Index		*LiDAR based* forest classes	*INCA based* simulated soil moisture 5d rainfall 3h rainfall intensity	coordinates

input variables

+

Landslide inventory

dichotomous response variable



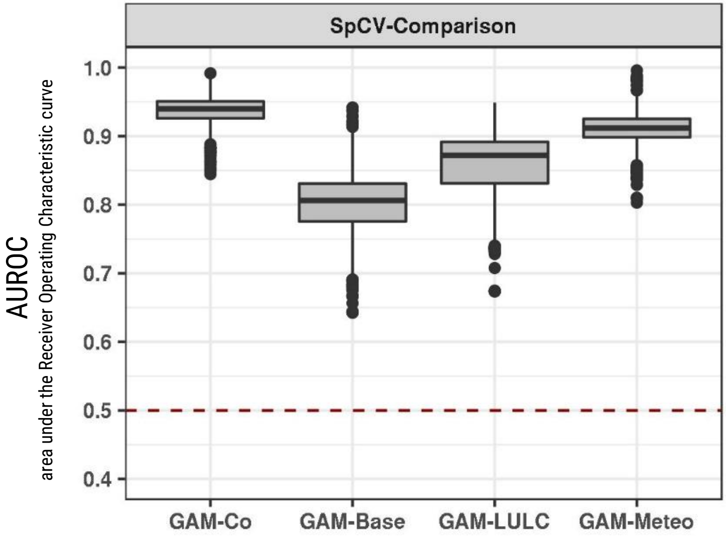
Model diagnostics
- Model performance
- Variable importance
- Predictor-response relationship

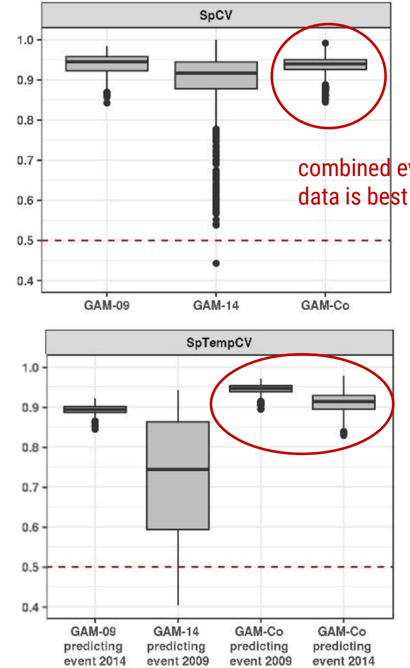
Model predictions
- Susceptibility storylines
- Uncertainties

Statistical approach

2 Model Diagnostics

***Q1**: What role do rainfall, soil moisture and LULC have in explaining landslides occurring during extreme weather events in the Styrian basin?*

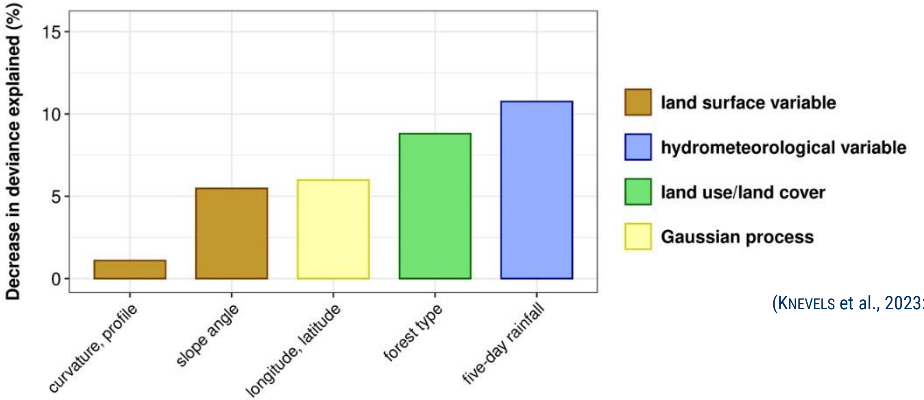




(KNEVELS et al., 2020: 11)

2 Model Diagnostics

***Q1**: What role do rainfall, soil moisture and LULC have in explaining landslides occurring during extreme weather events in the Styrian basin?*



(KNEVELS et al., 2023: 214)

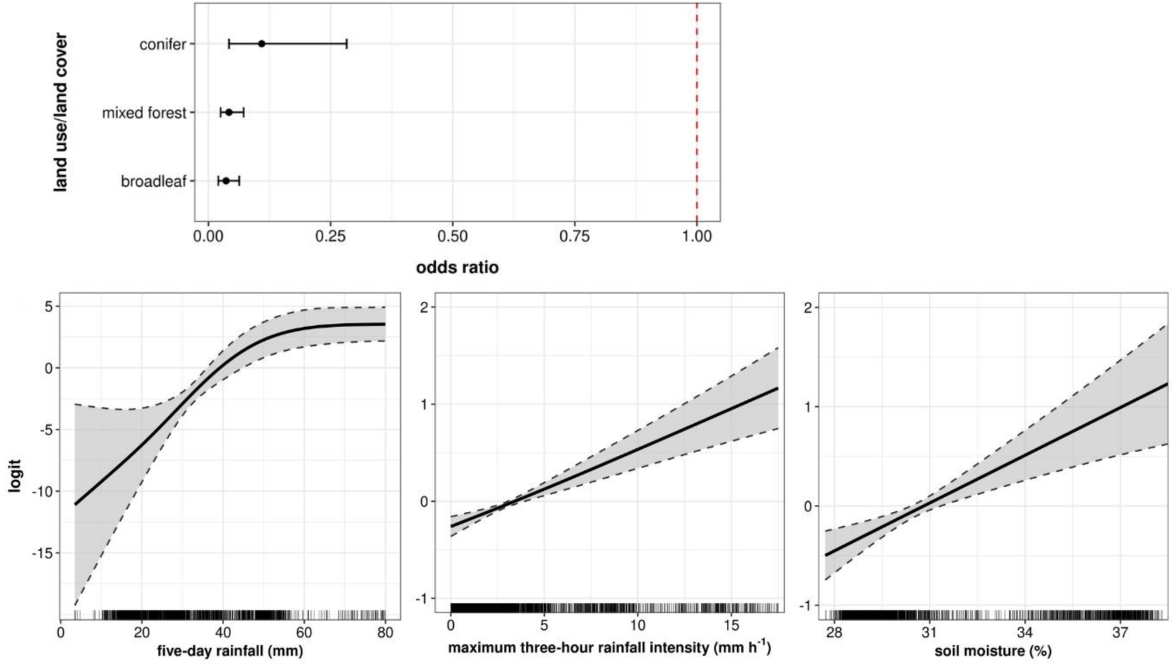
Variable	GAM-Spatial
Maximum 3 h rainfall intensity	0.85 (6)
Soil moisture	0.6 (9)

(rank of variable in parentheses, total of 18 variables)

(KNEVELS et al., 2023: 222)

2 Model Diagnostics

***Q1**: What role do rainfall, soil moisture and LULC have in explaining landslides occurring during extreme weather events in the Styrian basin?*



(KNEVELS et al., 2023: 214)

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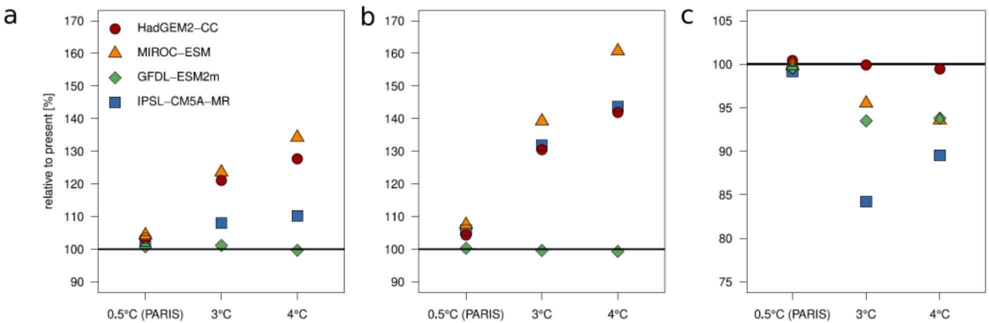
3 Landslides and Environmental Change

3 Environmental Change Data

- **Climate change data for 2009 event** (present-day 1975—2004 vs. future 2071—2100)



5-day rainfall | 3h rainfall intensity | soil moisture

Model	5-day rain	3-h rain	Soil moisture	Description
HadGEM2-CC	++	++	∘	much heavier rain
MIROC-ESM	++	++	-	much heavier rain, drier soil
IPSL-CM5A-MR	+	++	- -	heavier rain, much drier soil
GFDL-ESM2m	∘	∘	-	drier soil

++ strong increase, + increase, ∘ no change, - decrease, - - strong decrease.

(Maraun et al., 2022: 4f)

- **LULC change data**: proactive LULC management toward a climate-resilient mixed forest

(Maraun et al., 2022)

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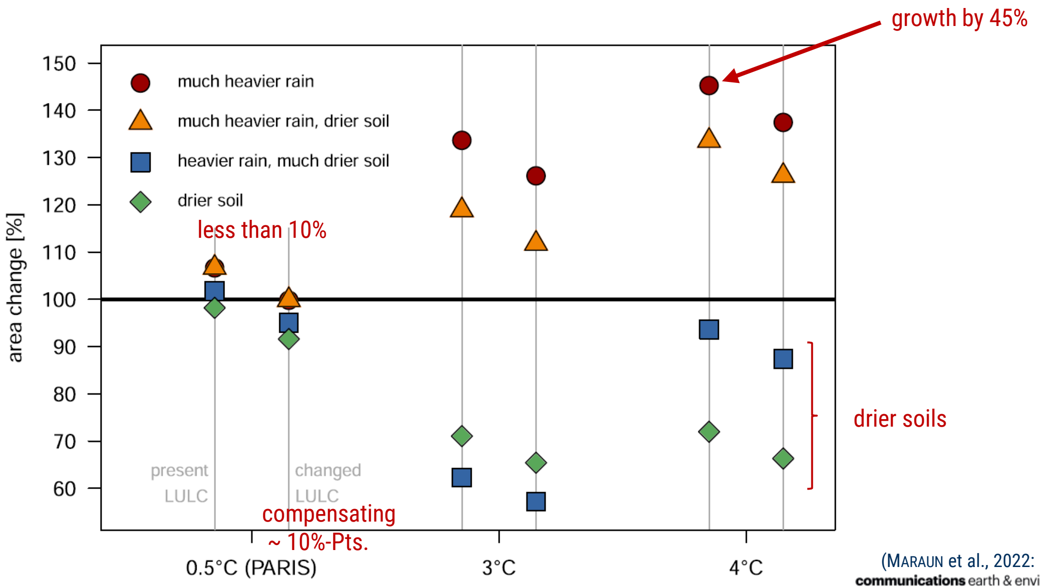
https://kajabi-storefronts-production.kajabi-cdn.com/kajabi-storefronts-production/blogs/34857/images/X1WKmTdqQJymmRf4OIhA_the_world_in_2100.png

3 Storylines of Landslide Susceptibility: Future

***Q2**: What effects do LULC and climate changes have on storylines of landslide susceptibility?*

high landslide susceptibility, 95th percentile of present climate

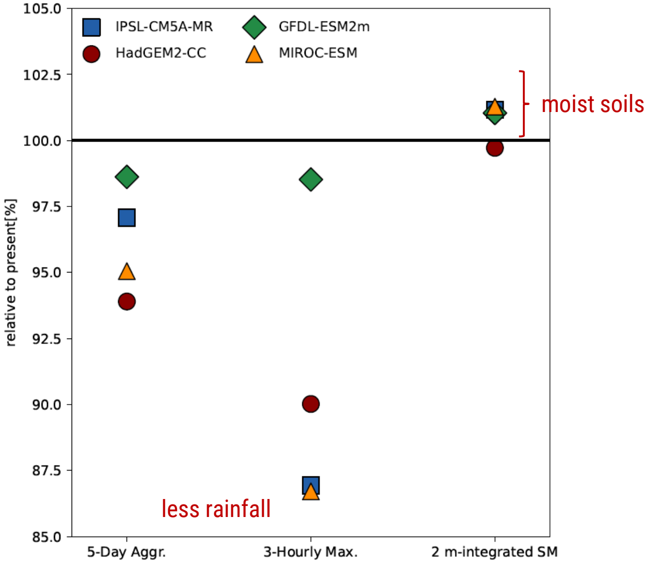


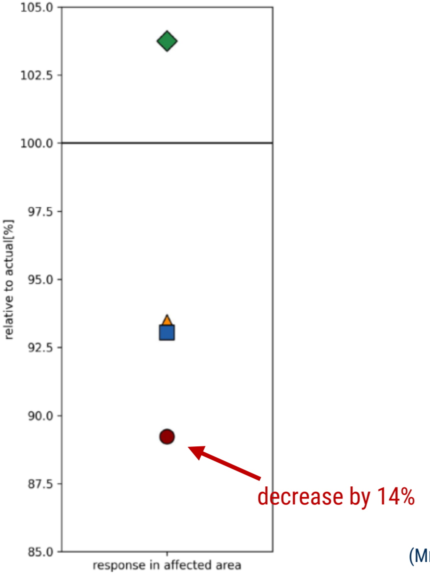
(MARAUN et al., 2022: 6)
communications earth & environment

https://www.museum-joanneum.at/fileadmin/_processed_/1/5/csm_lorenz-de-sype-und-wenzel-hollar_1620819061_0ca907c533.jpg

3 Storylines of Landslide Susceptibility: Pre-Industrial

***Q2**: What effects has climate change already had on landslide susceptibility?*



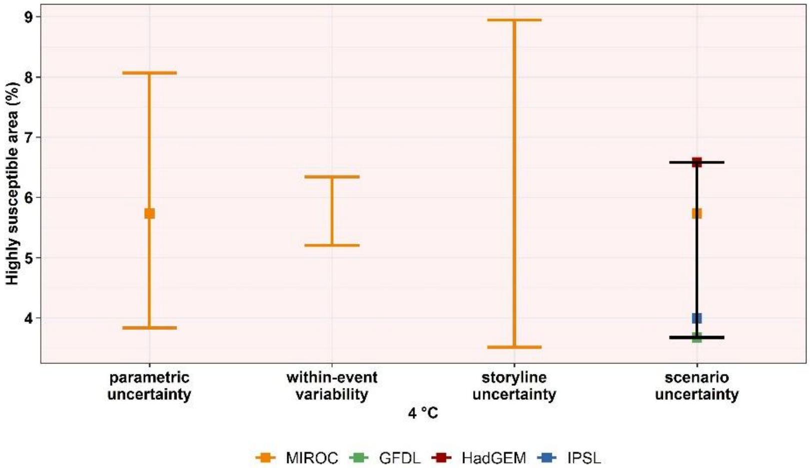


(MISHRA et al., under review)

3 Storyline Uncertainty

- Components of uncertainty (95% confidence interval)
  - **Landslide model** - Parametric uncertainty, $\boldsymbol{CI_{Lsl}}$ → Metropolis Hastings simulation of 10k GAMs
  - **Climate model**
    - Within-event internal variability, $\boldsymbol{CI_{IV}}$ → 2.5th/97.5th percentiles from 100 pairs
    - Scenario uncertainty, $\boldsymbol{CI_{CS}}$ → width of climate model signals in scenario

high landslide susceptibility, 70% of present-day observed landslides



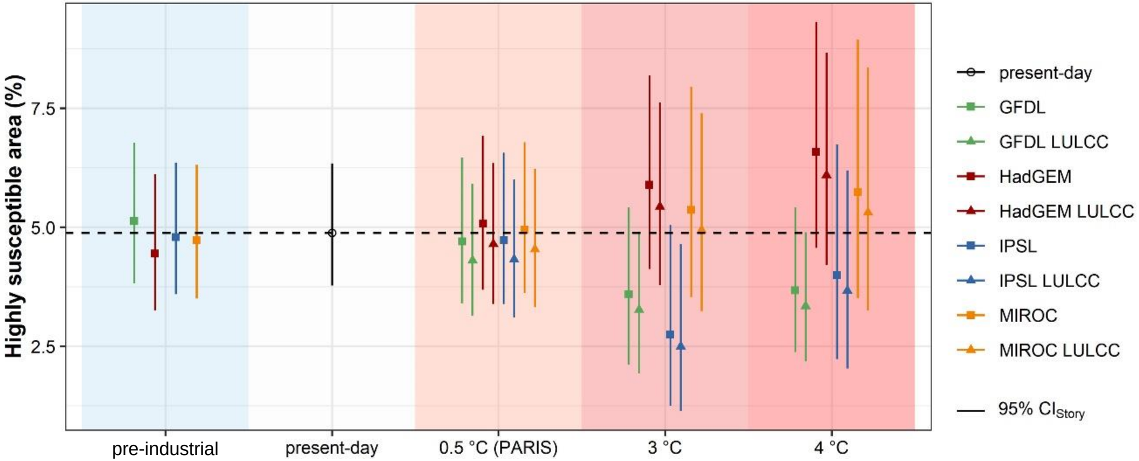
$$R_{\mathrm{IV;Lsl}} = \frac{\text{width of } \mathrm{CI_{IV}}}{\text{width of } \mathrm{CI_{Lsl}}}$$

$$R_{\mathrm{CS;Lsl}} = \frac{\text{width of } \mathrm{CI_{CS}}}{\text{width of } \mathrm{CI_{Lsl}}}$$

(Knevels et al., 2023)

3 Storyline Uncertainty

- ***Q3***: How uncertain are landslide susceptibility estimates emerging from an integrated modeling framework accounting for environmental change?

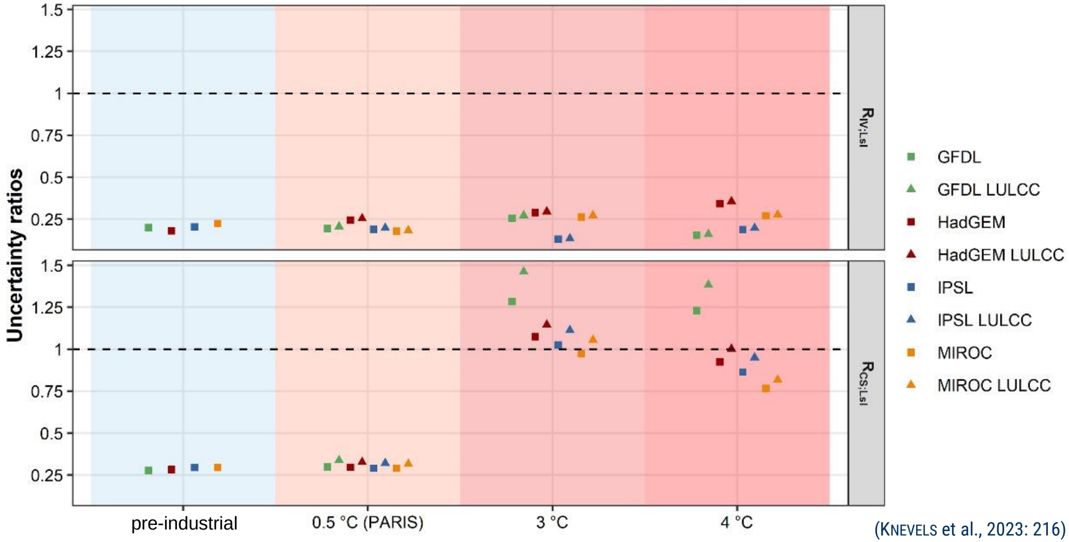


➢ Generally high storyline uncertainty increases even with higher warming levels

(KNEVELS et al., 2023: 216)

3 Storyline Uncertainty

- ***Q3***: How uncertain are landslide susceptibility estimates emerging from an integrated modeling framework accounting for environmental change?



(KNEVELS et al., 2023: 216)

➢ CI_{IV} substantially lower than CI_{LsI}

➢ CI_{LsI} of the same order as CI_{CS} for the higher warming levels (+3 and +4 K)

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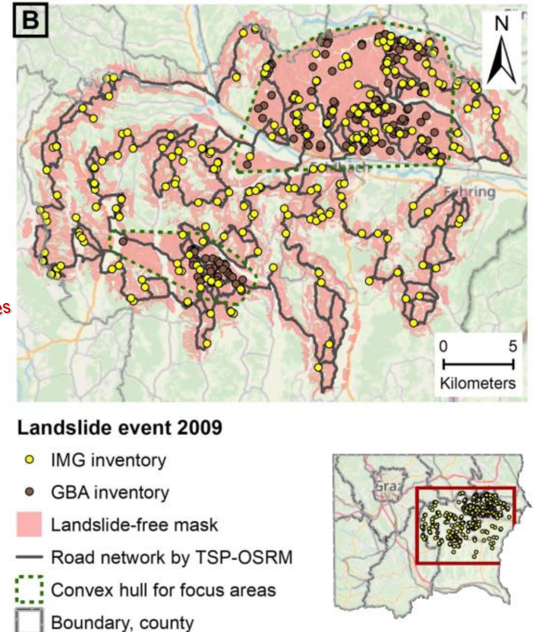
4 Achievements, Challenges, and Outlook

4 Achievements

- **Landslide susceptibility modeling**
  - ✓ Time-varying predictors to account for environmental change
    only 34% of landslide studies (REICHENBACH et al., 2018)
  - ✓ Reliable, physical-meaningful model for storylines
  - ✓ Profound model assessment (accounting for spatial data structure)
    only 60% (15%) of landslide studies (REICHENBACH et al., 2018)
  - ✓ Dated landslide data
  - ✓ innovative spatio-temporal approach for absence positioning

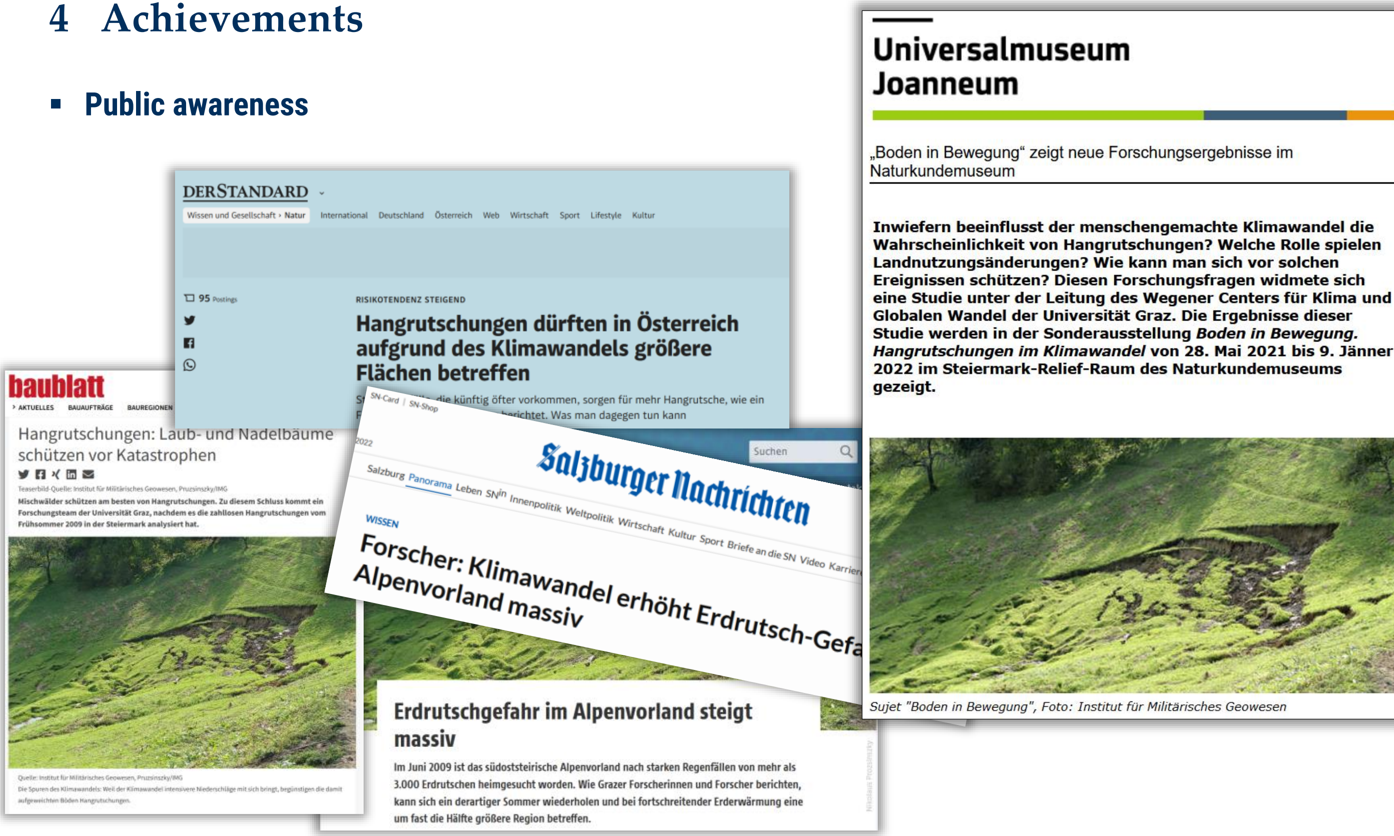


(KNEVELS et al., 2020: 7)

- **Climate model**
  - ✓ Convection-permitting climate models
  - ✓ Storyline coupled with delta change approach to ensure the high-resolution data basis

4 Achievements

- **Public awareness**



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95 Postings

RISIKOTENDENZ STEIGEND

Hangrutschungen dürften in Österreich aufgrund des Klimawandels größere Flächen betreffen

baublatt

› AKTUELLES BAUAUFTRÄGE BAUREGIONEN

Hangrutschungen: Laub- und Nadelbäume schützen vor Katastrophen

Teaserbild-Quelle: Institut für Militärisches Geowesen, Pruzsinszky/IMG

Mischwälder schützen am besten von Hangrutschungen. Zu diesem Schluss kommt ein Forschungsteam der Universität Graz, nachdem es die zahllosen Hangrutschungen vom Frühsommer 2009 in der Steiermark analysiert hat.

Quelle: Institut für Militärisches Geowesen, Pruzsinszky/IMG

Die Spuren des Klimawandels: Weil der Klimawandel intensivere Niederschläge mit sich bringt, begünstigen die damit aufgeweichten Böden Hangrutschungen.

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WISSEN

Forscher: Klimawandel erhöht Erdrutsch-Gefa
Alpenvorland massiv

Erdrutschgefahr im Alpenvorland steigt massiv

Im Juni 2009 ist das südoststeirische Alpenvorland nach starken Regenfällen von mehr als 3.000 Erdrutschen heimgesucht worden. Wie Grazer Forscherinnen und Forscher berichten, kann sich ein derartiger Sommer wiederholen und bei fortschreitender Erderwärmung eine um fast die Hälfte größere Region betreffen.

Universalmuseum Joanneum

„Boden in Bewegung" zeigt neue Forschungsergebnisse im Naturkundemuseum

Inwiefern beeinflusst der menschengemachte Klimawandel die Wahrscheinlichkeit von Hangrutschungen? Welche Rolle spielen Landnutzungsänderungen? Wie kann man sich vor solchen Ereignissen schützen? Diesen Forschungsfragen widmete sich eine Studie unter der Leitung des Wegener Centers für Klima und Globalen Wandel der Universität Graz. Die Ergebnisse dieser Studie werden in der Sonderausstellung *Boden in Bewegung. Hangrutschungen im Klimawandel* von 28. Mai 2021 bis 9. Jänner 2022 im Steiermark-Relief-Raum des Naturkundemuseums gezeigt.

Sujet "Boden in Bewegung", Foto: Institut für Militärisches Geowesen

4 Challenges and Outlook

- High uncertainty in the landslide model
  - more high-resolution data
  - more care and effort in recording landslides
  - landslide volume and size
  - improving landslide inventory using remote-sensing data

- Communication of *high susceptible area* → *x* number of landslides

(MISHRA et al., under review)

- Differentiation into more LULC classes and more LULC future scenarios would be desirable

- In-depth analysis of the 2014 event

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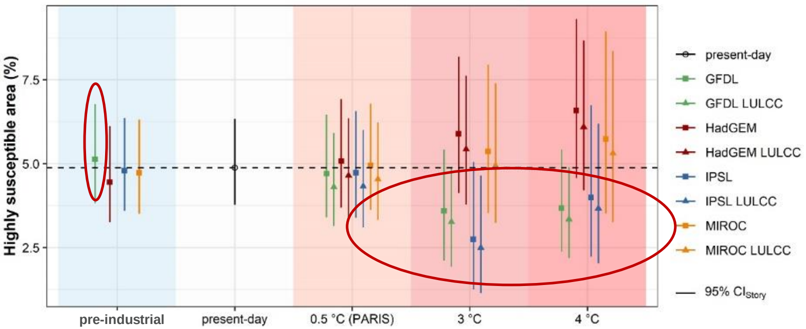
4 Challenges and Outlook



- "Cherry picking":
  Does climate change help us?

➢ dry spells followed by large precipitation increases landslide susceptibility

(Tichavský et al., 2019)

➢ desiccation cracks may lead to increased water infiltration

(Tichavský et al., 2019; Zhang et al., 2021)

➢ And what about other natural hazards or compound effects? – Fires, drying rivers, drought, enhanced hydrophobicity of soils leading to flooding (Milazzo et al., 2023)

EASICLIM-References

Knevels, R., Petschko, H., Proske, H., Leopold, P., Maraun, D., & Brenning, A. (**2020**). Event-based landslide modeling in the Styrian Basin, Austria: accounting for time-varying rainfall and land cover. *Geosciences*, *10*(6), 217.

Knevels, R., Petschko, H., Proske, H., Leopold, P., Mishra, A. N., Maraun, D., & Brenning, A. (**2023**). Assessing uncertainties in landslide susceptibility predictions in a changing environment (Styrian Basin, Austria). *Natural Hazards and Earth System Sciences*, *23*(1), 205-229.

Maraun, D., Knevels, R., Mishra, A. N., Truhetz, H., Bevacqua, E., Proske, H., ... & Puxley, B. L. (**2022**). A severe landslide event in the Alpine foreland under possible future climate and land-use changes. *Communications Earth & Environment*, *3*(1), 87.

Mishra, A. N., Maraun, D., Knevels, R., Truhetz, H., Proske, H., Brenning, A. (**submitted 2022**). Climate Change Amplified the 2009 Extreme Landslide Event in Austria. Submitted to *Climatic Change*. Under review.

References

Brabb, E. E. (**1984**). *Innovative approaches to landslide hazard and risk mapping*.

Cruden, D. M. , & **Varnes**, D.J. (**1996**). Landslide Types and Processes, Transportation Research Board, US National Academy of Sciences, Special Report, 247: 36-75. *Landslides Eng. Pract*, *24*, 20-47.

Fuchs, S., Wenk, M., & Keiler, M. (**2022**). Geomorphic Hazards in Austria. In *Landscapes and Landforms of Austria* (pp. 105-117). Cham: Springer International Publishing.

Gariano, S. L., & **Guzzetti**, F. (**2022**). Mass-movements and climate change.

Hornich, R., & **Adelwöhrer**, R. (**2010**). Landslides in Styria in 2009. *Geomechanics and Tunnelling*, *3*(5), 455-461.

Hovius, N., Stark, C. P., & Allen, P. A. (**1997**). Sediment flux from a mountain belt derived by landslide mapping. *Geology*, *25*(3), 231-234.

Knevels, R., Petschko, H., Leopold, P., & Brenning, A. (**2019**). Geographic object-based image analysis for automated landslide detection using open source GIS software. *ISPRS International Journal of Geo-Information*, *8*(12), 551.

Lima, P., Steger, S., & Glade, T. (**2021**). Counteracting flawed landslide data in statistically based landslide susceptibility modelling for very large areas: a national-scale assessment for Austria. *Landslides*, *18*(11), 3531-3546.

References

Milazzo, F., Francksen, R. M., Zavattaro, L., Abdalla, M., Hejduk, S., Enri, S. R., ... & Vanwalleghem, T. (**2023**). The role of grassland for erosion and flood mitigation in Europe: A meta-analysis. *Agriculture, Ecosystems & Environment*, *348*, 108443.

Reichenbach, P., Rossi, M., Malamud, B. D., Mihir, M., & Guzzetti, F. (**2018**). A review of statistically-based landslide susceptibility models. *Earth-science reviews*, *180*, 60-91.

Schweigl, J., & **Hervás**, J. (**2009**). Landslide mapping in Austria. *JRC Scientific and Technical Reports*.

Tichavský, R., Ballesteros-Cánovas, J. A., Šilhán, K., Tolasz, R., & Stoffel, M. (**2019**). Dry spells and extreme precipitation are the main trigger of landslides in Central Europe. *Scientific reports*, *9*(1), 1-10.

Wallemacq, P., Below, R., & McClean, D. (**2018**). *Economic losses, poverty & disasters: 1998-2017.* United Nations Office for Disaster Risk Reduction.

Wood, S. N. (**2017**). *Generalized additive models: an introduction with R*. CRC press.

Zhang, J. M., Luo, Y., Zhou, Z., Chong, L., Victor, C., & Zhang, Y. F. (**2021**). Effects of preferential flow induced by desiccation cracks on slope stability. *Engineering Geology*, *288*, 106164.

Thank you
for your attention!