Outcomes of a quantitative analysis of 46 soil chronosequence studies:

Vegetation plays the key role for rates of podzolization in most environments.

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KEYWORDS

soil-forming factors, podzolization, soil formation, soil chronosequences, statistical modeling

HIGHLIGHTS

- We generated a database of published studies on Podzol development in humid mid and high latitudes.
- First quantitative analysis of factors affecting the rate of podzolization using statistical models.
- Age and vegetation have stronger effects on the rate of podzolization than texture and climate.
- The model captured the accelerating effect of conifers on podzolization.

1. INTRODUCTION

Over the past decades, many Podzol studies showed that diverse combinations of soil-forming factors (Jenny 1941) lead to great variability concerning rates of soil-formation.

Several, partially contradictory, theories exist for the mechanisms of mobilization and immobilization involved in podzolization (Lundström et al., 2000; Sauer et al., 2007).

But there is a general consensus about **the factors favoring podzolization**:

- **cool, humid climates** (precipitation >> evaporation) where water regularly moves down the profile (Koutanemi et al., 1988),
- **cool temperatures** that decrease biological activity and thus delay litter decomposition (Schaetzl and Isard, 1996),
- **thicker, more persistent snowpacks** that lead to less soil freezing and larger, faster fluxes of infiltration during the snowmelt (Schaetzl, 2002; Schaetzl et al., 2018; Schaetzl and Isard, 1996);
- **vegetation producing acidic litter** such as conifers, heather or oaks (Bain et al., 1993; Lichter, 1998),
- **quartz-dominated, sandy soils** (Stützer, 1998),
- **low iron content of the parent material**, because parent materials with high contents of iron oxides can buffer the system and thus counteract acidification (Duchaufour and Souchier, 1978).

Despite this basic agreement the relative importance of the individual factors and especially their combined effects have not yet been quantified.

Therefore, this study aimed to quantify the effects of the various factors

(i) **On the soil age at which podzolization first becomes visible, and**

(ii) **On the rates of podzolization thereafter.**

2. METHODS

To quantify the effects of the various soil-forming factors, published soil chronological sequence studies were compiled and systematically statistically analyzed.

The open-source software environment R was used for all statistical computing and graphics.

a. DATA SOURCES AND COMPILATION

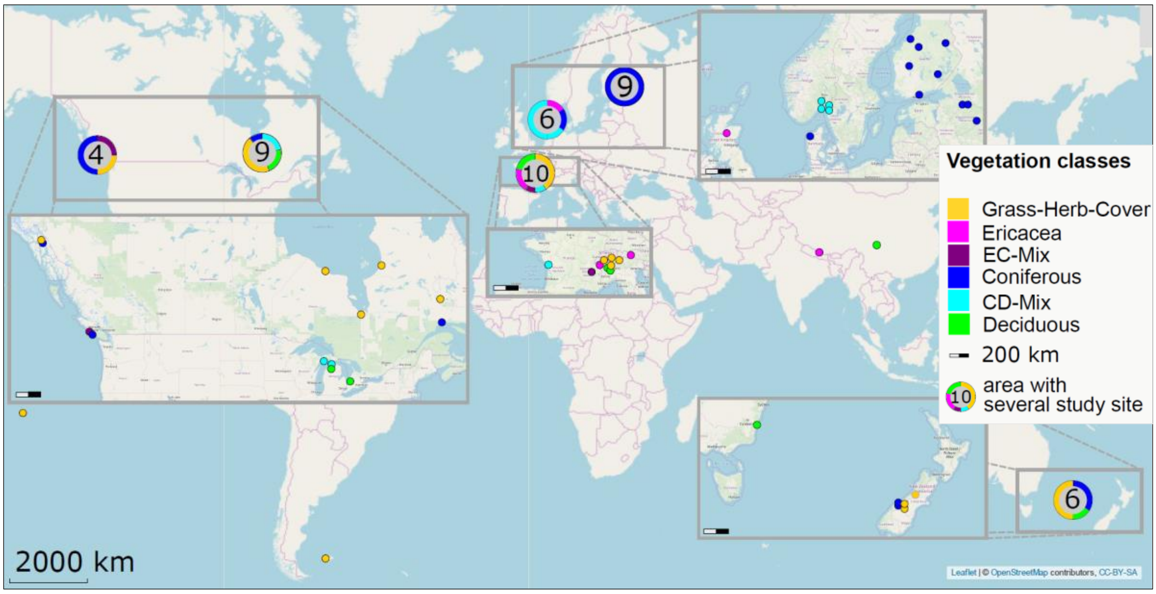


Figure 1. Locations of the 46 study areas with 231 dated profiles and predominant vegetation in each study area. (Zwanzig, 2020)

Restrictions for profiles:

- Just Holocene profiles, to avoid major changes in climate and vegetation
- All profiles have to be in the humid mid and high latitudes, because the number of dated Holocene tropical Podzols is very limited
- comprehensible information on environment and soil analysis, since the results of each study have to be comparable

After the data exploration and the check of statistical dependencies eight variables are transferred to the statistical model *(Figure 2)*:

Notes on the selection of variables:

- **E horizon *(EHorizon)* occurrence and thickness** was chosen as response variables since they are one of the few features that were described in all 46 studies and are one important aspect of podzolization
- **Mean annual precipitation *(map)*** and the **difference between minimum and maximum monthly mean temperature *(trange)*** were used to capture the effect of the climate

- **Vegetation class *(vegetation class)*** – subdivided in “Grass-Herb-Cover” *(pioneer)*, “Deciduous” *(deciduous)* and “Coniferous and mixed Vegetation” *(coniferous &mixed)* – was used to cover the effect of the vegetation
- **mean sand content in the upper 50 cm in % *(sand)*** was used to cover one aspect of parent material
- **age of the soil in years *(age*)** was used to cover the effect of time
- The name of the study area *(site)* was chosen as random factor
- Longitude and latitude *(long and lat)* were used to identify statistical dependencies

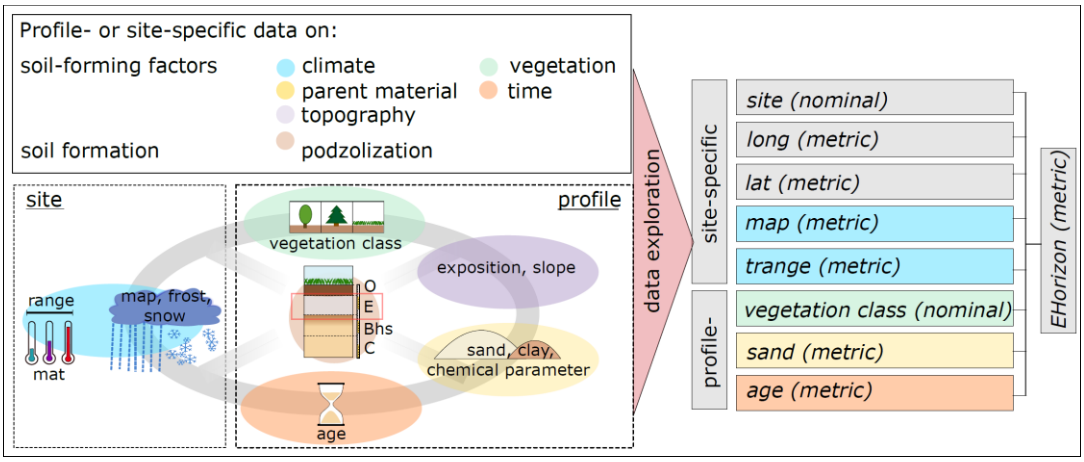


Figure 2. Sketch of the data structure. Different variables had to be excluded after data exploration. Please notice the difference between profile and site-specific information. (Zwanzig, 2020)

Other variables had to be excluded because they contain too many zeros, they are highly collinear or there is not enough information on the variable available.

b. STATISTICAL MODEL

Because E horizon thickness exhibits a zero-inflated (semi-)continuous distribution attempts to model the response variable E horizon thickness with an ordinary linear regression model and a linear mixed-effects model failed.

We handled this issue by considering

(i) a binary process that generates the zero values and

(ii) a process defining the non-zero distribution.

3. RESULTS AND DISCUSSION

We used a zero-altered gamma (ZAG) model consisting of

(i) A Bernoulli part: binomial part to model the probability of E horizon presence under various environmental conditions

(ii) A Gamma part: including zero-truncated data to model the influence of the various factors on the E horizon thickness.

The two-model approach showed that (figures 3 – 6):

- besides soil **age**, the effect of **vegetation predominates** over all other influencing factors
- **coniferous and mixed vegetation** are the factors that most strongly enhance podzolization
- **climatic factors** mean annual precipitation and range of mean monthly temperatures are **less important**, both for the onset of podzolization and the increase in E horizon thickness over time
- there was **no effect of sand content** captured in the dataset

But still keep in mind that:

- there are of course **much interaction between the soil-forming factors**, like between vegetation and climatic factors or parent material
- all **soils** in our database were from environmental settings that **basically meet the conditions for Podzol formation** and thus
- our model did **not show all expected enhancing effects of individual factors** on podzolization

  e.g. sand content: Almost all soils were characterized by high sand contents. This reflects that this criterion has to be met for Podzol formation and the model just did not identify any further enhancing effect.
- Unfortunately, due to a lack of data, some influencing factors could not be considered (e.g. snow, iron content)

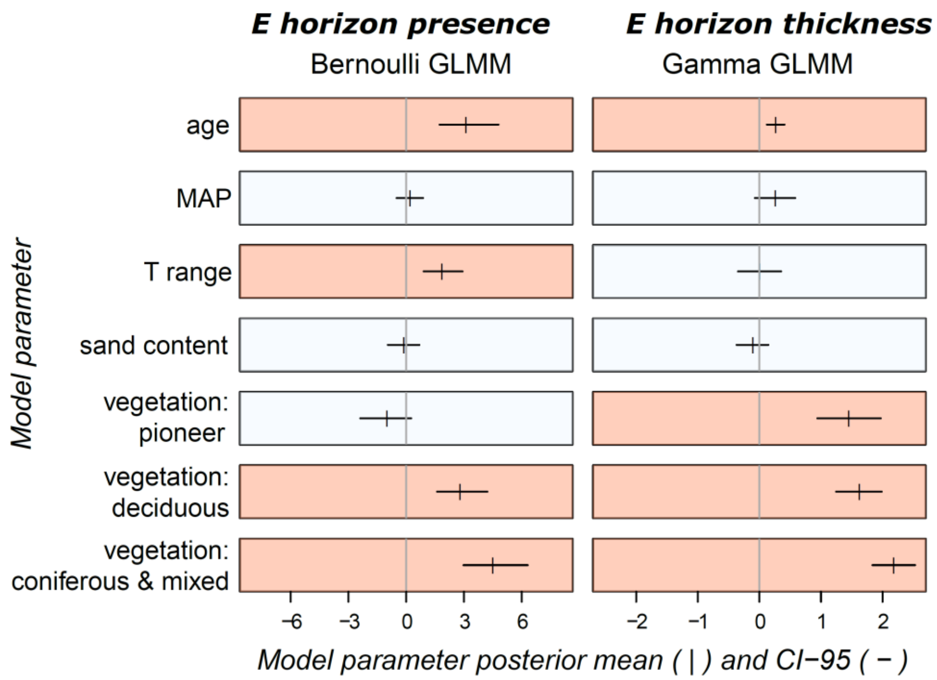


Figure 3. Magnitude and direction of the effects of the soil-forming factors explained by single covariates of the Bernoulli GLMM (left) and the Gamma GLMM (right). (Zwanzig, 2020)

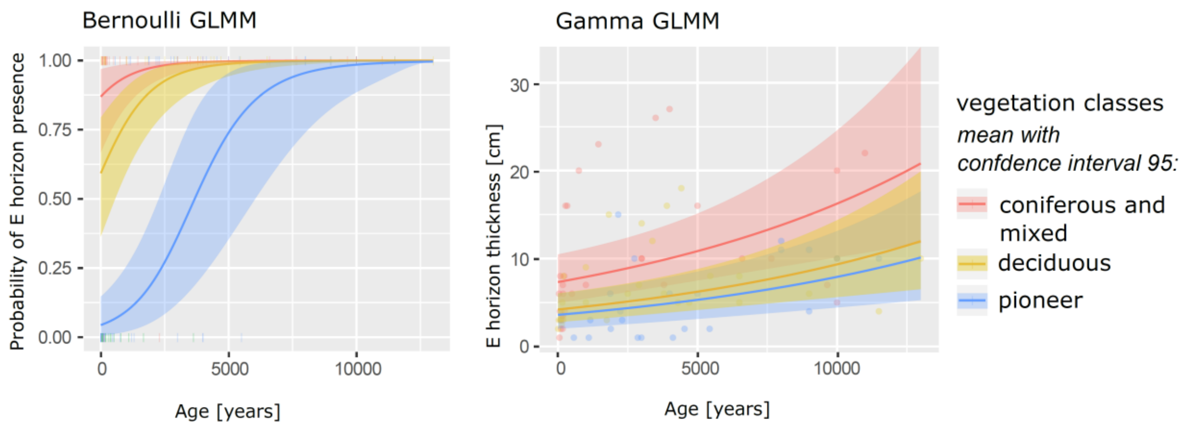
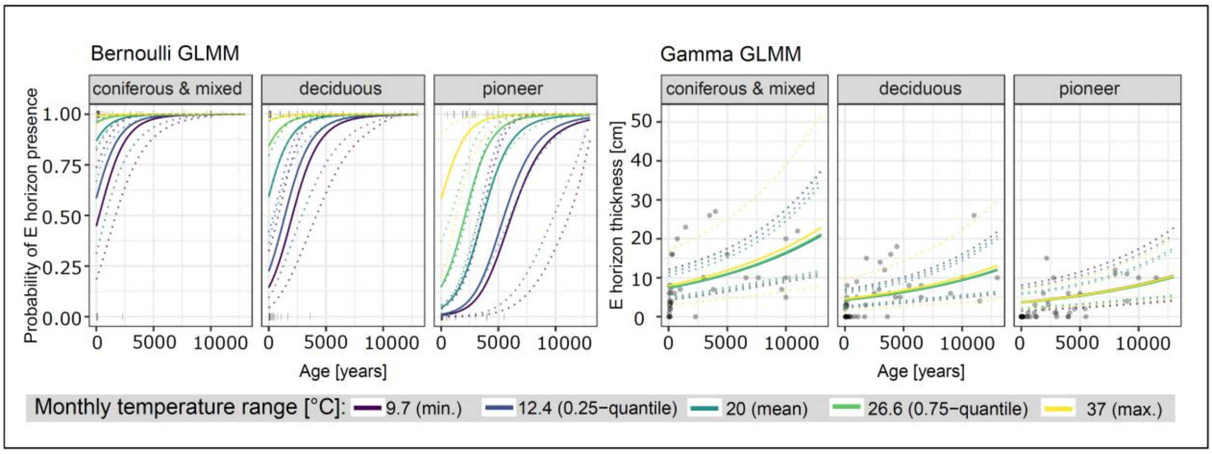


Figure 4. Modeled effect of vegetation on the probability of the occurrence of an E horizon (left) and E horizon thickness (right) with soil age. Please note that the sigmoidal curves in the Bernoulli GLMM that represent the fit of each vegetation class (left) only approach the probabilities of 0 and 100%. This is a common feature of Bernoulli models.



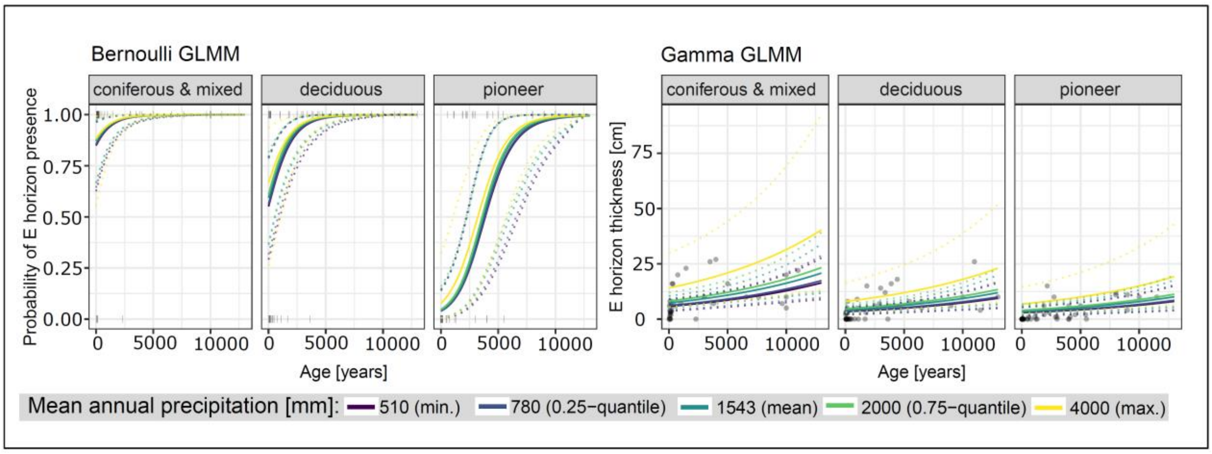


Figure 5. Modeled effect of climate (range of min/max, monthly mean temperature and mean annual precipitation) on podzolization.

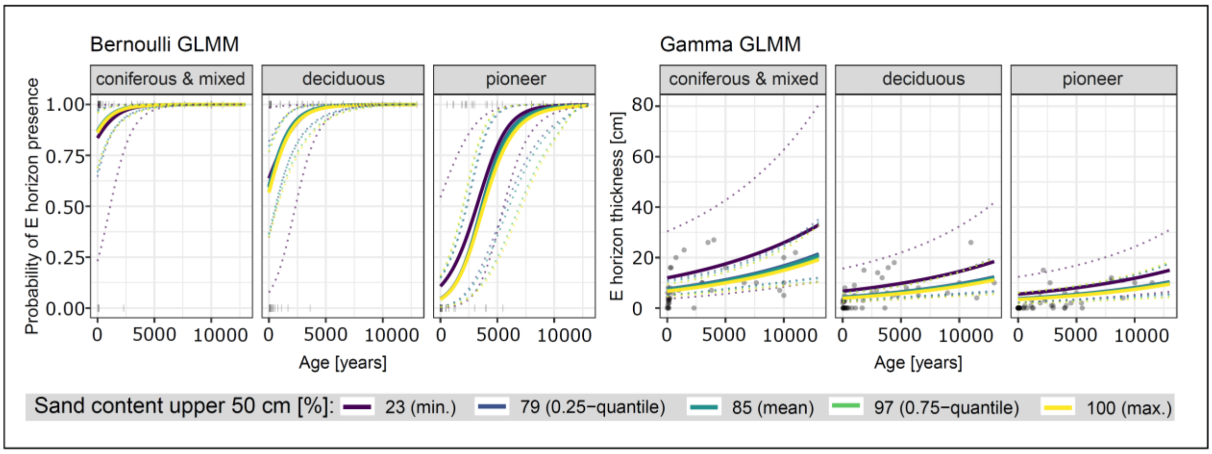


Figure 6. Modeled effect of parent material (sand content) on podsolization

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