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Combining quantitative (palaeo-)pedological, palaeo-environmental studies and modelling – an important step on the way to predict soil reactions to environmental change

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Abstract
A study on a Holocene soil chronosequence in S-Norway is used to test the capability of the model SoilGen to model the development of soils with clay illuviation. SoilGen models soil formation as a function of the soil forming factors. Thus, the latter had to be reconstructed for the time span of soil development. The factors 'relief' and 'parent material' were obtained by field and laboratory analyses, the factor 'time' was derived from existing sea level curves, and the factors climate and organisms were obtained from literature and from a recent palaeo-environmental study. The chronosequence has been established on loamy marine sediments, and shows Albeluvisol development with time. Clay illuviation starts within 1650 years. The characteristic albeluvic tongues start to form after 4600 to 6200 years. They develop preferably along cracks. Albeluvic material falls into the cracks, leading to the development of albeluvic tongues, which become deeper and wider with time. Development of pH, CEC and clay content with time as measured in the investigated pedons is compared with the model results in order to check, to which degree model results agree with observed results.

Key Words
Interdisciplinary approaches, soil development, Albeluvisols, modelling, prediction, environmental change.

Introduction
Soil formation is the result of the co-action of the soil forming factors climate, organisms, relief, parent material and time (Jenny 1941). Consequently, any environmental change will inevitably cause a reaction of soil systems. These reactions are not linear. In a stable system, alteration of environmental conditions may proceed for some time, having minor effects on soils, which may even not be recognised. However, when a certain threshold of environmental change is exceeded, a minor further alteration may lead to a sudden response of soil systems. Such response may include negative effects such as loss of organic matter, erosion and, in some regions, salinisation and desertification. Thus, regarding the proceeding climatic and environmental changes, one of the primary present tasks in soil science is the prediction of possible soil alterations in changing environments. Understanding, quantifying and modelling soil development under known environmental conditions is an important step on the way to quantitative prediction of soil reactions to changing conditions. This step however requires interdisciplinary collaboration between scientists investigating actual and past development of soils and environmental conditions in the field and laboratory on one hand, and scientists developing quantitative models of soil development on the other hand. This paper gives an example for such collaboration and finally points out to other interdisciplinary collaborations, which may contribute to the task of future soil alteration prediction.

Methods
Study area
The study area selected for this project is located in the Norwegian counties Vestfold and Østfold, on both sides of the Oslo Fjord (Figure 1), and provides ideal conditions for quantitative pedogenetic studies. Scandinavia is in general characterised by glacio-isostatic uplift since the glacier retreat at the termination of the last glacial period, and relative sea level curves have been established for several areas along the coast. The curves for the Oslo Fjord coast show a continuous relative sea level fall throughout the Holocene. Due to the steadiness of this process, no separate terraces were formed, but soils continuously get older from the

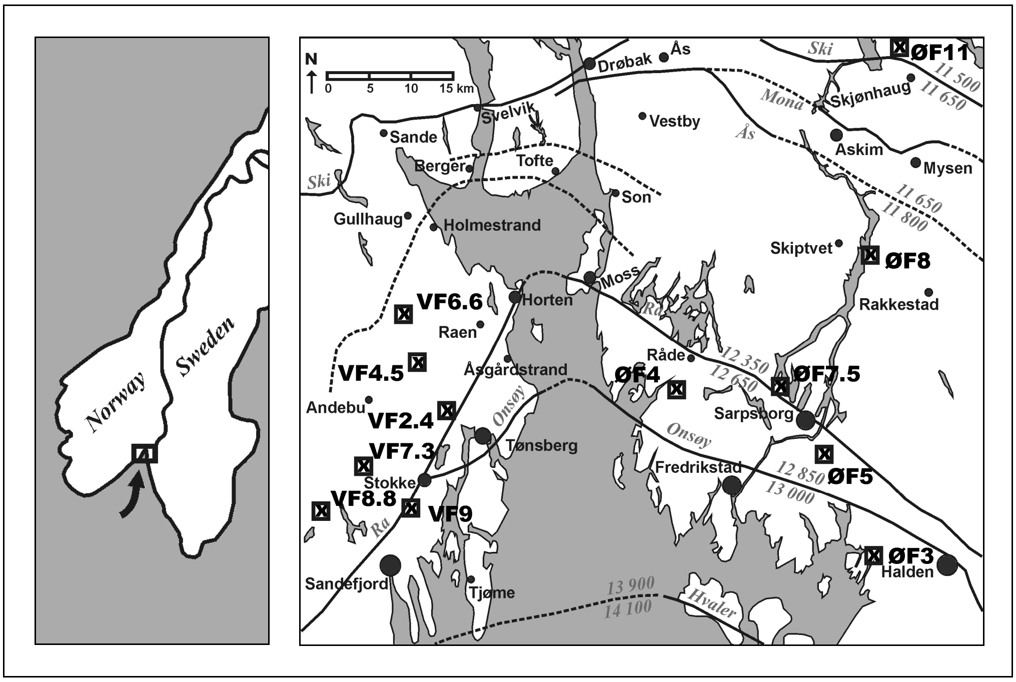

Figure 1. Location of the study area (left) and pedons (right) (Sørensen 1979; 1992). Black lines indicate locations of moraines; the time spans of moraine formation are indicated in cal yrs BP (after Ramberg *et al.* 2006). At the time of glacier retreat, the whole area was below sea level.

coast towards the inland. The mean annual temperature ranges from 5.4 to 6.0 °C. Precipitation is 975 – 1094 mm/year in Vestfold and 751 – 829 mm/year in Østfold. Palaeo-climate and palaeo-vegetation reconstruction for the period of soil formation were based on literature data (Hafsten 1956; Danielsen 1970; Henningsmoen 1980; Birks *et al.* 1994; Hammarlund 2003; Nesje *et al.* 2004; Bakke *et al.* 2008; De Jong *et al.* 2009) and on results of a recent study (Sørensen *et al.* in prep.).

Field methods

Two soil chronosequences comprising six pedons each, were established, one in Vestfold (with land surface ages ranging from 1,650 to 9,000 years) and one in Østfold (3,000 – 11,050 years). The ages were estimated by use of sea level curves established for several locations in the area, based on calibrated radiocarbon datings (Hafsten 1979; Henningsmoen 1979; Sørensen *et al.* 1987, 2007; Sørensen 1999). The parent material is loamy marine sediment. The geological basement below the sediment consists of basic magmatite (monzonite, latite) in Vestfold and predominantly acid magmatite (granite) in Østfold.

Laboratory methods

The samples were air-dried and passed through a 2 mm sieve. All analyses were carried out on air-dried fine earth using two replicates. The results were converted to 105 °C dried soil. pH (H_2O) was measured with a glass electrode at a soil:solution ratio of 2.5:1. Carbon contents were measured by a Leco CN-analyser and considered as organic carbon (OC), since the soils contained no carbonates. Particle size analysis was done by sieving (sand fractions) and pipette method (silt and clay). Samples with > 1 % organic matter were treated with H_2O_2 prior to particle size analysis. Cation exchange capacity (CEC) was determined according to Chapman (1965) at pH 7. The total element composition of the samples was determined by X-ray fluorescence analysis of fused discs (without replicate).

Modelling approach

The model SoilGen (Finke and Hutson 2008) was used to simulate the evolution of various soil characteristics over time as a function of the soil forming factors. Parent material composition enters the model as initial condition. Precipitation, potential evapotranspiration, water table depth, rain water composition and air temperature are all derived from climate reconstructions and enter the model as boundary conditions for the simulation of water, solute and heat flow. Slope gradient, aspect and prevailing wind can be included to modify these values to local exposition if needed, and erosion and sedimentation events can be handled as well. Vegetation development according to the climatic evolution provides input of organic matter, which is simulated to gradually decompose and mineralise, in the process producing CO_2 and releasing cations and anions previously uptaken by plants. Simulated partial CO_2-pressure profiles govern calcite dissolution chemistry and pH. Chemical equilibria of various Ca, Na, K and Mg species as well as exchange equilibria between these cations are calculated. Bioturbation profiles are linked to vegetation type to simulate redistribution of organic matter, mineral and chemical components in the topsoil. Clay migration is simulated as a detachment process in the bare part of the topsoil by rainsplash impact, followed by dispersive transport and accumulation deeper in the profile, where dispersive conditions cease. Dispersive conditions can occur at any depth, if ionic strength is low, and bi- and trivalent cation concentrations in the soil solution are low. The model uses soil pH as a proxy for dispersive/non-dispersive conditions. Physical particle deposition is implemented as a filtering process subject to velocity of water percolation. The model is thus in principle capable to calculate decalcification and the development of Ah, E and Bt horizons. We applied the model onto the Vestfold and Østfold datasets to verify, if observed soil development can be reproduced by such models.

Results

Within 1650 years the soils show horizon differentiation into A, E and B horizons, indicating limited water permeability of the fine-textured sediments (Figure 2). E horizons become lighter in colour with time. In Vestfold, the youngest, 1650 year-old soil (VF2.4) has clay coatings. In Østfold, no clay coatings have been found in the youngest, 3000 year-old soil (ØF3), but pH (H_2O) in the E horizon is suitable for clay illuviation (pH 5.1). Clay content shows a maximum in the Btg horizon, and it is assumed that clay illuviation has taken place, but its morphological evidence is masked by the groundwater influence at the depth of clay accumulation. The pH (H_2O) values of the lower parts of the E horizons are still within the pH interval suitable for clay illuviation, pH 6.5-5, in almost all pedons, so that it can be concluded that clay illuviation has been active until present in all soils studied.

Formation of the characteristic albeluvic tongues starts after 4600 to 6200 years of pedogenesis. The tongues develop preferably along cracks. In horizontal sections, these cracks occur as polygons. The cracks are already present in the youngest soils. They are due to shrinking of the marine sediments as the water-saturated sediments are lifted above groundwater level. Later, the cracks continue to develop due to repeated wet/dry and freeze/thaw cycles. Albeluvic material falls or is washed into the cracks, leading to the development of albeluvic tongues, which become deeper and wider with time.

1650 year-old soil (VF 2.4): Endogleyic Luvic Cutanic Stagnosol (Endoeutric, Siltic).

6200 year-old soil (VF 6.6): Cutanic Epistagnic Albeluvisol (Endoeutric, Profondic, Siltic).

11 050 year-old soil (ØF 11): Cutanic Epistagnic Albeluvisol (Endofluvic, Siltic, Protospodic).

Figure 2. Progressive soil development on loamy marine sediment in southern Norway.

The fresh sediment (C horizon of pedon VF4.5) has pH (KCl) 6.8 and pH (H_2O) 7.8. pH in the upper 25 cm (weighted mean) shows a strong decrease in the first time and a very slight decrease after about 2000 years, which can be best described by logarithmic functions. Between 1650 and 9000 years, pH (KCl) is 3.3-4.0 and pH (H_2O) is 4.0-5.0 in Vestfold; pH (KCl) is 3.2-3.5 and pH (H_2O) is 4.0-4.7 in Østfold. The pH variability seems to be rather related to vegetation cover than to the factor time in these soils.

Conclusion

Progress within each discipline of soil science has led to increasing specialisation and separation of the disciplines. This trend is inevitable and irreversible, because further progress can be achieved only by high degree of specialisation. However, most major environmental problems require interdisciplinary approaches, due to the complexity of the affected systems. This means that an effort to actively cross the boundaries between disciplines is needed. Combination of quantitative studies on soil development, palaeo-environmental reconstruction and modelling is an important step on the way to predict soil system reactions to changing environmental conditions. Other interdisciplinary approaches may contribute, e.g. combination of studies on paleosols and lake sediments or other palaeo-archives, which enables deciphering of soil reactions to environmental changes in the past.

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Directed variability of paleosols properties in short chronosequences studied by the statistical approach (a case-study of kurgans in Orenburg region, Russia)

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Abstract

The relative chronology of kurgans (burial mounds) construction in two ancient cemeteries was established by studying the properties of paleosols buried under kurgans. This chronology has been later confirmed by the radiocarbon dating of humus and carbonates from the paleosols. The paleoenvironmental reconstruction based on paleosols properties changes the influence of their spatial variability. Soil group composition was based on principal component and cluster analyses and using the relative values for each paleosol property on the basis of correlation with modern background soil-analogue. The differences in humus and carbonate supplies in paleosols are statistically reliable for "short"chronosequences with 100-150 years duration.

Key Words

Paleosols, chronosequences, kurgans, paleoclimatic reconstruction, Holocene, directed variability of soil properties, relative values.

Introduction

At present, large-scale researches of paleosols buried under archaeological monuments (burial mounds or kurgans) in the steppe area of Russia are carried out aiming at the reconstruction of paleoenvironmental and climatic conditions for the second part of Holocene. Schemes of soil evolution and reconstructed paleoclimatic conditions as a result of these researches both for the same region and for the steppe zone as a whole do not coincide in many cases and are often contradictory. The possible reasons of these discrepancies, in our opinion, can be (1) study of paleosols buried under archaeological monuments of the same culture as a uniform indicator of conditions of the environment for a whole epoch (while various cultures functioned) and (2) not taking into consideration the variability of properties of paleosols buried under kurgans of the same culture as a result of climatic fluctuations having a shorter time scale.

We offer the special approach where paleosols buried under kurgans of the same archaeological culture in a studied burial ground are considered as a short chronosequence (Khokhlova *et al.* 2007). The assumption considers that kurgans in the large burial grounds constructed by ancient people belonged to one archaeological culture and had appeared step-by-step during the existence of the given culture. The under-kurgan paleosols are divided into groups by similarity of their properties within one group, and then we try to determine a relative or absolute chronological order of burial of soils and a construction of kurgans in a burial ground on the basis of archaeological data or radiocarbon dating. When we deal with short time intervals of functioning of burial grounds (100-200 years) the spatial variability of soil properties can make difficulties for revealing their variability connected with changing climatic conditions in the period of paleosol burial. For the decreasing of influence of spatial variability, it is proposed to calculate the relative values for each paleosol property on the basis of correlation with modern background soil-analogues. Searching for a modern soil-analogue for each paleosol is carried out on the basis of similarity of their particle-size pattern. One modern soil-analogue may be in agreement with any group of paleosols if they are similar on the basis of particle-size distribution.

Natural conditions of the study site

The paleosols studied are buried under kurgans in two burial grounds of the Orenburg region. Within the Chernozem-steppe belt of the Orenburg region, the climate is the warmest and driest in the study area: the mean temperature of January is –15°C, and that of July is +22°C. The mean annual precipitation is about 350 mm; evaporation exceeds precipitation by 1.5 times. Among the unfavorable climatic phenomenon is the periodical high temperature on the soil surface. Sometimes in June-July this temperature reaches to 65°C and higher. The characteristic sign of the soils in the Orenburg steppe is taken to be a tongue-like lower boundary of humus horizon. The cracking of soil mass due to continental climate, very high soil surface temperatures in summer and filling up the cracks with humus material are common. Vegetation of the non-arable sites is represented by steppe communities with the predominance of feather grass and fescue.

Results and discussion

In the Skvortsovsky burial ground two kurgans (№.3 and 4) referred to early narrow chronological horizon of the Timber Grave archaeological culture, 18^{th}-17^{th} centuries BC, have been studied. Each of two kurgans had mounds consisted of two layers and two paleosols buried under both the central (first) and peripheral (second) mound layers. That the peripheral mound layer was built after the central one is unambiguously visible in stratigraphy of the each earth mound studied. This case has been used for modeling since at construction of short chronosequence from the Timber Grave paleosols we were guided by the given or known order of paleosol burial and could understand the reliability of differences in chemical properties of paleosols in the constructed chronosequence on the basis of a statistical approach. The absolute and relative (comparatively with modern soil-analogue) values of storage of humus and carbonates for 0-100 and 0-180 cm thickness were examined in the paleosols. The received differences for "extreme" paleosols in a short chronosequence are statistically reliable. The order of construction of different layers of kurgan mounds studied is in agrrement with radiocarbon dating of pedogenic carbonates. It has been fixed that from the beginning to the end of the Timber Grave Time examined there was an accumulation of humus and leaching of carbonates in soils and the climate varied in the direction favorable for the life of the nomadic population – a fall of temperature and increase of precipitation. As mentioned before, the study site is situated in modern dry-steppe area with high summer temperatures with a precipitation deficiency.

The Fillipovka 1 burial ground was situated 200 km to west from the Skvortsovsky one and functioned during the period of the Early Sarmatian culture – from the middle of the 5^{th} till the middle or the end of the 4th centuries BC. The lithological background on which soils in burial ground territory developed differed considerable in diversity and influenced the considerable spatial soil property variability. Therefore the identification of paleosol groups and their modern soil-analogues has been carried out using cluster analysis and principal component analysis (PCA). 10 cm intervals of modern soils were chosen for PCA. Exchangeable cations (bases), carbonate content and particle-size pattern have been used as variables for the PCA, because these properties could be related with depth of the entire soil profile. The first main component is completely defined by lithological features of the layer. These results have been compared to cluster analysis results based on the profile distribution of one property - the content of particles size less than 0.01 mm. The results were in close agreement, but in the last case they were less stable and depended on the selected joining rule. Therefore, for further analysis the results obtained by PCA have been used and the clusters formed by modern soils and paleosols have been established. For each of the clusters, only one modern analogue for paleosols was chosen, the closest one.

Differences of environmental conditions have been revealed by comparison of differences of humus, carbonate and sum of the exchangeable cation storages in paleosols and their modern analogues. Within the period of the Filippovka 1 burial ground functioning, one group of kurgans were built in more "arid" environmental conditions (the first early group of kurgans), and other one – in more «humid» environmental conditions (the second, latter group of kurgans). In paleosols buried under kurgans of the early group in comparison with paleosols of the latter one, the decrease of humus storage in the upper part of profile and increase of carbonate and the exchangeable cations, specifically Ca storage in the middle part of the profile are statistically reliable.

It was shown that the proposed approach together with the standard approaches – archaeological and radiocarbon dating, can be used for reconstruction of the order of kurgans construction on the basis of the variability of properties of paleosols buried under kurgans. Special attention should be given to the fact that differences in humus and carbonate contents (the basic profile-forming properties in steppe soils) that are statistically reliable in paleosols of short chronosequences that functioned within 100-150-200 years.

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Genesis and composition of paleosols and calcretes in a plio-pleistocene delta fan of the Costa Blanca (SE Spain)

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Abstract
A plio-pleistocene alluvial fan with a vertical series of 7 fossil soils and 7 calcrete complexes was investigated at the Spanish south-eastern coastline. Alternating sedimentation and soil formation suggest repeated cyclical climatic changes during the Late Pliocene and Early Pleistocene. The red paleosols and pedogenic calcretes developed under subtropical and Mediterranean conditions while the (soil) sediments and synsedimentary calcretes represent a (semi)arid climate.

Key Words
Paleopedology, calcretes, stratigraphy, climate change, Mediterranean.

Introduction
Calcretes in the alluvial fan near Campoamor in SE Spain have attracted several geological, geomorphological and pedogenetic studies (Rutte 1958; Rohdenburg and Sabelberg 1969; Blümel 1982). Calcretes are formed by surface cementation, subterranean crusts, surface (lamellae) crusts or subterranean lamellae crusts (Rutte 1958, 1960). Such processes were most likely favoured during moist interglacials, with emphasized seasonal fluctuations favouring the downward movement of seepage water in decalcified soils (Rohdenburg and Sabelberg 1969). Rubefication in paleosols and calcrete formation are however not related processes in this alluvial fan (Blümel 1982). This work includes a pedological and climatic interpretation of the soils in Campoamor and a detailed description and classification of the according calcretes. They are further compared with soils and calcretes in the Basin of Granada/Andalusia (Günster and Skowronek 2001) to substantiate previous findings of climatic development in the western Mediterranean by soil stratigraphy.

Methods
Texture, clay mineralogy, iron oxides, chemical composition and micromorphology of paleosols and calcretes were described according to standardized laboratory methods.

Results
Macroscopic description
The about 30 meters high cliff profile includes 7 fossil soils and 7 calcrete complexes exposed to the south. Strata are easily differentiated macroscopically by their colour and structure. The upper four meters of this soil-sediment-sequence are made up by a calcrete complex (k1) of at least four genetic stages. The following 20 meters are dominated by sandy, red (pedogenic?) calcretes, but also include intermediate conglomerates and (soil) sediments. Calcretes are mainly structured into two (k2, k3, k5) or three (k4) parts with a soft and nodular crust base, a harder top and a lamellae crust. The lower part of the cliff profile displays the marine regression during the late Pliocene. The following carbonate complex (k7) is a pseudo-conglomerate closing with fine-sandy (dune) sediments in the lower bed. Calcretes are described as Ck (K) horizon, the f prior to B or C horizons stands for the term “fossil” according to the German soil classification.

It results in the following fine stratigraphy of the cliff profile:

Depth(m)	Horizon		Description
0–0.50	Ck(K)	k1	pink (5YR7/3) and pinkish white (5yr8/2) calcrete; fluidal structure; coherent
–1.00	2Ck		pink (5YR8/3) carbonate cementation of conglomerate
–2.70	3Ck(K)		reddishbrown (2.5YR5/4) calcrete; fluidal structure; coherent
–4.00	4Ck(K)		pinkishwhite (5YR8/2) calcrete; chalk-like, soft
–4.50	1.fBwt-Bc		red (2.5YR4/8), carbonatic, gravel-free sandy clay loam; subpolyedric
–5.00	Ck(K)	k2	pink (5YR7/3) calcrete; coherent
–5.50	2Ck(K)		pinkish white (5YR8/2) calcrete; subangular blocky
–6.50	3Ck		yellowish red (5YR5/6), extremely calcareous, slightly gravelly silty clay loam; polyedric; (soil)sediment
–6.90	2.fBvt-Bk		dark yellowish brown (10YR4/6), strongly calcareous, slightly gravelly clay loam; subpolyedric
–7.50	Ck(K)	k3	pink (5YR8/4) calcrete; coherent
–8.00	2Ck(K)		pink (7.5YR8/4) calcrete; subangular blocky
–9.00	3.fBt		dark yellowish brown (10YR4/6) non-calcareous, gravel-free loamy sand; subangular blocky
–9.20	2Ck(K)	k4	light reddish brown (5YR6/4) calcrete; layered (coherent)
–10.20	3Ck(K)		pink (7.5YR8/4) calcrete; layered (coherent)
–11.20	3Ck(K)		pink (7.5YR8/4) calcrete; subangular blocky
–12.30	4Ck		reddish yellow (5YR6/8), strongly calcareous, slightly gravelly loamy sand; subangular blocky and layered (coherent); (soil) sediment
–12.60	5Ck		pink (5YR8/3) carbonate cementation of conglomerate
–13.40	4.fBwt		dark yellowish brown (10YR4/6), non-calcareous, gravel-free sandy loam; subangular blocky
–13.90	Ck(K)	k5	pink (5YR8/4) calcrete; layered (coherent)
–15.00	2Ck(K)		pink (5YR8/4) calcrete; fine-grained; layered (coherent)
–15.20	5.fBwt1		red (2.5YR5/6), non-calcareous, gravel-free silty clay loam; subangular to angular blocky
–16.20	2Bwt2		dark yellowish brown (10YR4/4), non-calcareous, gravel-free silty clay loam; angular blocky
–17.10	Bk		pink (5YR8/4) and red (2.5YR5/6) lime accumulation; angular blocky
–17.60	6.fBwt-Bk		dark yellowish brown (10YR4/4), strongly calcareous, slightly gravelly loam; angular blocky
–19.80	2Bk		pink (5YR8/4), extremely calcareous, slightly gravelly clay loam; angular blocky
–20.40	7.Bwt		red (2.5YR5/6), non-calcareous, slightly gravelly loamy sand; subangular blocky
–21.20	2Bk		pink (2.5YR8/4), extremely calcareous, slightly gravelly clay loam; angular blocky
–22.50	3Ck(K)	k6	light red (2.5YR6/7) calcrete; fine-grained; layered (coherent)
–23.80	4Ck(K)		light red (2.5YR6/8) calcrete; layered (coherent)
–24.80	4Ck(K)	k7	white (10YR8/1) calcrete; chalky; layered (coherent)
–27.60	5Ck(K)		pinkish white (2.5YR8/2) calcrete; sandy; layered (coherent)
–29.10	6Ck(K)		white (2.5YR8/0) calcrete; sandy; layered (coherent)
>29.10	7Ck(K)		light reddish brown (5YR6/4) carbonatece mentation of conglomerate; fluidal structure; load casts

Texture and chemistry

The textural distribution in decalcified soil is quite heterogeneous, with 16.7-86.5 % of sand, 3.7-49.3 % silt and 9.7-44.4 % clay (Table 1), while the mean values are 50.7 % (sand), 23.3 % (silt) and 26.0 % (clay). Sand domination can be ascribed to calcarenites of Pliocene age which have developed in the alluvial fan. Clay neogenesis can be deduced by distinctly higher clay contents in the soils (29 % average) as compared to the (soil) sediments (17 % average). Soil and (soil) sediment texture typically represent middle and lower (delta) alluvial fans.

Table 1. Grain size distribution of the soil and (soil) sediments [weight-%].

	Horizon	Gravel	CS	MS	FS	Sand	CSi	MSi	FSi	Silt	Clay
1.	fBwt-Bk	0.0	0.0	19.2	40.6	59.8	6.7	1.2	1.2	9.1	31.0
	3Ck	2.9	0.0	14.1	34.1	48.2	16.5	5.2	3.7	25.4	26.4
2.	fBwt-Bk	2.7	0.0	15.2	29.0	44.2	19.3	5.3	5.5	30.1	25.7
3.	fBwt-Bk	0.0	0.0	21.9	42.0	63.9	8.9	1.6	1.1	11.6	24.4
	3Ck(K)	0.0	0.0	42.5	36.9	79.4	2.9	1.6	1.4	5.9	14.6
	4Ck	0.0	0.1	60.1	26.3	86.5	3.2	0.4	0.1	3.7	9.7
4.	fBwt	0.0	0.1	20.3	30.5	50.9	16.0	9.2	5.2	30.4	18.6
5.	fBwt1	0.0	0.0	29.3	31.9	61.2	8.0	2.6	2.1	12.7	26.0
	2Bwt2	0.0	0.0	9.2	19.1	28.3	12.8	7.4	6.9	27.1	44.4
6.	fBwt-Bk	7.2	0.0	9.1	17.4	26.5	24.1	14.1	11.1	49.3	24.2
	2Bk	4.6	0.0	4.3	12.4	16.7	27.7	10.6	9.2	47.5	35.7
7.	fBwt	2.4	0.0	34.3	37.7	72.0	6.2	1.7	2.5	10.4	17.5
	2Bk	2.4	0.0	8.0	14.0	22.0	12.6	15.0	12.1	39.7	38.3

The pH values vary between 6.9 and 8.4 (Table 2) and well reflect de- and recalcification processes, since sediments (pH >7.8) and decalcified horizons (pH <7.6) can be differentiated from recalcified soil horizons (pH 7.7). Pedogenic iron oxides are rather rare with proportions of 0.003-0.084 % for the oxalate-soluble (Fe_o) and 0.10-1.10 % for the dithionite-soluble fraction (Fe_d). This is due to small concentrations of total iron (Fe_t) with a maximum of 1.49 % (Table 2). Small Fe_o/Fe_d ratios (0.030-0.086; Table 2) document the high crystallinity in the paleosols and (soil) sediments, while Fe_d/Fe_t ratios around 1 (Table 2) reflect advanced weathering. Intense reddening can be ascribed to the presence of hematite and a close correlation between Fe_d and redness rating according to Torrent *et al*. (1980, 1983) (r=0.72; n=13).

Table 2. Chemistry of the soil and (soil) sediments.

	Horizon	pH	$CaCO_3$(%)	Fe_o(%)	Fe_d(%)	Fe_t(%)	Fe_o/Fe_d	Fe_d/Fe_t
1.	fBwt-Bk	7.9	6.2	0.027	0.59	1.03	0.045	0.57
	3Ck	7.9	38.1	0.022	0.38	0.90	0.059	0.41
2.	fBwt-Bk	7.8	10.2	0.044	1.03	0.91	0.042	1.13
3.	fBwt-Bk	7.5	0.0	0.024	0.76	0.98	0.031	0.77
	3Ck(K)	8.1	38.7	0.006	0.12	0.35	0.050	0.34
	4Ck	8.4	34.7	0.003	0.10	0.27	0.030	0.37
4.	fBwt	7.4	0.0	0.037	1.10	0.91	0.033	1.20
5.	fBwt1	7.2	0.0	0.024	0.49	1.49	0.048	0.35
	2Bwt2	6.9	0.0	0.084	0.97	0.94	0.086	1.03
6.	fBwt-Bk	7.6	32.3	0.039	0.78	0.94	0.050	0.82
	2Bk	7.8	55.9	0.019	0.35	0.96	0.055	0.35
7.	fBwt	7.2	0.0	0.020	0.35	1.00	0.057	0.35
	2Bk	7.6	27.3	0.046	0.69	0.94	0.066	0.73

Clay mineralogy

The semi-quantitative composition of clay minerals in the soils and (soil) sediments is fairly uniform with illite (55-68 %) and smectite (20-37 %) dominance. They are inversely correlated (r=0.78; n=13). Chlorite and vermiculite (3-5 %) are identified in three horizons only. Kaolinite (3-13 %) is more common in Bwt horizons which may infer a neoformation during pedogenesis. It is however not clear whether this can be ascribed to parent material inheritance and/or alteration and neoformation under similar climatic conditions.

Carbonates

Calcretes contain 19.5-51.5 % Ca and 0.11-0.29 % Mg, with Ca/Mg ratios between 121 and 319. Dominant calcite and quartz may overlap (minor) smectite XRD peaks from random powders. A phreatic or lacustrine origin of the calcretes in the delta fan of Campoamor can be excluded. The colour of the calcrete dissolution is mainly between 5YR, 7.5YR and 10YR (only the synsedimentary calcrete (k7) and the conglomerate have colours of 5Y and 2.5Y, respectively). Since the carbonate dissolution contains only 0.01-0.11 % iron, the enrichment of carbonate-bound iron and following reddening mainly result from parent material detachment.

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Micromorphology
Clay illuviation is indicated by thin iron oxides and clay coatings. Clay minerals (smectite in particular) were destroyed by intense shrink-swell processes inducing stress cutans which characterise changing wet and dry conditions. Since microstructure, colour, type and number of pedofeatures differ within the crust, the various parts reflect different pedogenetic stages. The lack of pedogenic features in the calcrete therefore clearly results from sedimentation.

Discussion and conclusions
The paleosols and calcretes in the delta fan of Campoamor were compared with alluvial fans of the Granada Basin (250 km to the south-west). The latter have developed between the Late Pliocene and Early Pleistocene. By comparison of both areas, the paleosols from Campoamor are distinctly further developed. This is clearly expressed by higher Fe_d/Fe_t ratios, a more intense rubefication and pronounced plasma mobility. The fossil soils of Campoamor are comparatively sandier with a more pronounced rubefication (i.e. redness rating). Because of the small specific surface of the sand, minimal amounts of iron oxides (Fe_d=0.35) are most likely sufficient for intense reddening. This is further supported by a high permeability and aeration of the substrate. Soil development can therefore be ascribed not only to climatic differences, but also to intense genesis as referred to parent material. Whereas the calcretes in the soils of the Granada Basin are (monogenetic) crusts according to Günster (1999), the differentiated composition of calcretes in Campoamor is a polygenetic product. Surface erosion and sedimentary fossilization were followed by secondary carbonatization and subsequent induration. Consequently, the latter represents at least two pedodynamic periods. At least 15 stages of soil formation can be reconstructed. While subtropical-mediterranean conditions supported pedogenetic processes, the accumulation of (soil) sediments and genesis of synsedimentary calcretes occurred under considerably drier, (semi-)arid conditions.

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Landscape - Soilscape Evolution Modelling: LAPSUS

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Abstract
Landscape evolution modelling can make landscape evolution hypotheses explicit and theoretically allows for their falsification and improvement. Ideally, landscape evolution models (LEMs) combine the results of all relevant landscape forming processes into an ever-adapting digital landscape (e.g. DEM). These processes may act on different spatial and temporal scales. LAPSUS is an example of such a LEM. In multiple study cases different landscape processes have been included in LAPSUS: water erosion and deposition, landslide activity, creep, solifluction, weathering, tectonics and tillage. Besides properties of soils influencing landscape forming processes, vegetation effects can also be included. Process descriptions are kept as simple and generic as possible, ensuring wide applicability of the modelling approach. Interactions between processes are turn-based: soil redistribution caused by one process are calculated and used to adapt the DEM before another process is simulated. LAPSUS uses multiple flow techniques to model flows of water and sediment over the landscape. Though computationally costly, this gives a more realistic result than steepest descent methods. In addition, the combination of different processes may create sinks during modelling. Since these sinks are not spurious, the model has been adapted to deal with sinks in natural ways. This is crucial for several purposes, for instance when studying damming of valleys by landslides, and subsequent infilling of the resulting lake with sediments from upstream.

Key Words
Landscape Evolution Modelling, LAPSUS, soil redistribution, erosion.

Introduction
This short paper summarizes ongoing and completed work with the LAPSUS model and foreseen developments in the near future. LAPSUS is a landscape evolution model (LEM) that combines the effects of multiple landscape forming processes, including soil formation, into one dynamic landscape modelling framework. Spatial and temporal extent and resolution may vary from slope, catchment to basin, processed grid cells from 1 to 1000 m^2, timesteps of multiple events, seasons, years, decades and simulation periods from years to millennial time scales.

Interactions between processes are turn-based: soil redistribution caused by one process are calculated and used to adapt the DEM before another process is simulated. In multiple study cases different landscape processes have been included in LAPSUS : water erosion and deposition, landslide activity, creep, solifluction, weathering, tectonics and tillage. (Figure 1).

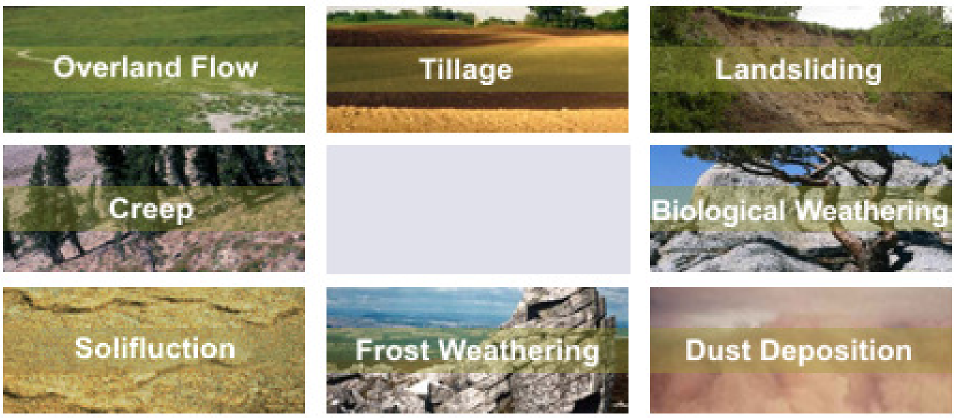

Figure 1. Overview of processes incorporated in the LAPSUS modelling framework (see also www.lapsusmodel.nl).

Besides properties of soils influencing landscape forming processes, vegetation effects can also be included. Process descriptions are kept as simple and generic as possible, ensuring wide applicability of the modelling approach. LAPSUS uses multiple flow routing techniques to model the flow of water and sediment over the landscape. This is computationally costly, but yields a more realistic result than steepest descent methods, especially when combining multiple processes over multiple timesteps.

The combination of different processes may create sinks during modelling. Since these sinks are not spurious, the model has been adapted to deal with them in a natural way. This is crucial when studying damming of valleys by landslides, and subsequent infilling of the resulting lake with sediments from upstream.

Results and discussion

LAPSUS has been used for erosion and landscape evolution studies in many landscapes in many countries over the last years. The development of LAPSUS started in 2000 with the programming, calibration and validation of the LAPSUS model and applications concerning land use in Spain and Ecuador (Schoorl *et al*. 2000, 2002, 2004, 2006; Schoorl and Veldkamp 2001, 2006). Later, the model has been extended in order to include soil redistribution by landsliding in New Zealand and Taiwan (Claessens *et al*. 2005, 2006a, 2006b, 2007a, 2007b). In addition, issues of DEM resolution and the treatment of sinks and pits in the landscape have been investigated (Temme *et al*. 2006, 2009a) as well as stretching the models time scale to landscape evolution time spans, for example in South Africa (Temme and Veldkamp 2009; Temme *et al.* 2009b). Different applications with individual processes have been developed, for example, the model has been used in regional nutrient balance studies in Africa (Haileslassie *et al*. 2005, 2006, 2007; Roy *et al*. 2004; Lesschen *et al*. 2005). The model has also been applied in desert environments in Israel (Buis and Veldkamp 2008);it has been used in combination with geostatistical tools and tillage in Canada (Heuvelink *et al*. 2006), and to investigate the faith of phosphor in the landscapes of the Netherlands (Sonneveld *et al*. 2006).
Recent developments and directions with the LAPSUS model are:

- Connectivity, agricultural terraces and land abandonment (Lesschen *et al*. 2007, 2009).
- Interactions and feedback mechanisms between land use and soil redistribution (Claessens *et al*. 2009).
- Effects of hydrological engineering on soil redistribution in large fluvial systems (Viveen *et al*. 2009)
- Erosion in a landscape evolution context, comparing event based and long term based models: LISEM and LAPSUS (Baartman *et al*. 2009).
- Refining the LAPSUS temporal resolution. Modelling daily sediment yield from a meso-scale catchment, a case study in SW Poland. (Coevert-Keesstra *et al*. 2009)
- Land sliding in mountainous areas. Landscape Dynamics: Calibrating landscape process modelling with Caesium-137 data, separating water driven erosion from landslides? See (Schoorl *et al*. 2009).
- 3D river gradient modelling. Quaternary tectonics, sea level and climate change: the case of the river Miño (Viveen *et al*. 2009).
- Coupling and interaction with TOA modelling. A novel site-specific methodology to assess the supply curve of environmental services (Stoorvogel *et al*. 2009; Claessens *et al*. in prep).

Conclusion

Landscape evolution modelling allows for confirmation, falsification or improvement of landscape evolution hypotheses and can make the consequences temporally and spatially explicit. Ideally, landscape evolution models (LEMs) combine the results of all relevant landscape forming processes into an ever-adapting digital landscape model These processes may act and interact on different spatial and temporal scales. The LAPSUS modelling framework is an example of a LEM that has embedded multiple landscape forming processes and their interactions in a generic tool that can be used to study many landscapes of the world at multiple temporal and spatial scales.

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Long-term soil landscape modelling in a Mediterranean agricultural environment

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Abstract

Nowadays, soil is subjected to rapid evolutions induced by climate changes and humans disturbances. Modeling is an appropriate methodology to analyse, understand space time evolution in soil and landscape processes and to test the effect these climatic and anthropogenic variations on soil cover evolution at short and medium term. And indeed to propose future technologies and landscape management practices to conserve soil. This study presents the LandSoil model, which is an event based model, dimensioned for fine spatial [1 m] and medium [10 –100 years] temporal scales, taking into account a detailed representation of the agricultural landscape structure. The aims of this research were to use pedological knowledge coupled with the LandSoil model to simulate soil evolution as affected by soil redistribution processes e.g. water-erosion processes and mechanical erosion. The model has been calibrated and validated under the current environmental conditions and landscape structure. Results confirm the observed patterns in terms of soil development and redistribution, as well as the preponderant effect of landscape structures to reduce climatic effects.

Key Words

Quantitative pedology, quantitative modelling, landscape evolution, landscape scale, long-term soil redistribution modelling, soil erosion, tillage erosion.

Introduction

Early soil scientists had already sought to identify the dynamic dimension of soils (Dokuchaev 1883; Kossovich 1911; Shaw 1932). Soil evolution over time was integrated as a factor of soil formation by Jenny (1941, 1961). This perception of soil evolution over time, often achieved at the profile scale, was accessed during last decades by studies focusing on quantitative pedology at the landscape scale. It appears that soils and landscapes evolve simultaneously (Hall, 1983): soil organization evolution is mainly controlled by soil redistribution processes due to water and tillage erosion (Hairsine and Rose 1992a; 1992b; Lindstrom *et al.* 1992; Quine *et al.* 1999), influenced by topographic and climatic parameters, but with a major contribution of management strategies. The perennial landscape features have also a strong influence on soil spatial distribution (geometry) and soil genesis (Follain *et al.* 2006).

In recent studies, soil was subjected to rapid evolutions. Two ways of fast soil cover changes can be identified: changes induce by climate and those induce by humans. Human induced changes are those which can be implemented by the farmers individually at the field or farm scale and those which can be imposed by policy- and decision-makers (land planners, natural resource managers) at a range of scales (farm, municipality, catchments, region). Climate induced changes are those related to changes in the seasonal distribution of climate factors and in the frequency of extreme events predicted by the projections of future climate change.

All theses fast modifications may have large consequences on cultivated ecosystem productivity and impose wider use of technologies and landscape management practices to conserve soil. Modeling is an appropriate methodology to analyse, understand and simulate space time evolution in soil and landscape processes. We need quantitative models for soil formation and distribution in the landscape to test the effect of different scenarios of land management and climate evolutions.

In recent years, landscape modelling (Coulthard 2001; Willgoose 2005) has been a matter of increasing interest for many researchers, with a few models focused on agricultural environment evolution. The intended uses of these models were to predict and manage erosion and the transport of soil matter on the terrain surface. The cumulative effect of erosion and sediment yield has been considered as a key to understanding landscape evolution.

Geo-morphological modelling is a topic of research that takes into account the main hydrological and sediment erosion transport rules to describe the processes and evolution of terrain physiography. Some recent models deal with soil redistribution under agricultural practices such as SPEROS (Van Oost *et al.* 2000; Van Oost *et al.* 2005a; 2005b; Govers *et al.* 2006), based on the Watem/Sedem model (Van Oost *et al.* 2000; Van Rompaey *et al.* 2001). Other modelling study proposed soil mechanistic model combining soil redistribution processes and soil production function at the landscape scale (Minasny and McBratney, 1999, 2001). These modelling gives an evaluation of soil redistribution utilizing mechanistic rules for diffusion and water erosion (Kirkby 1985) and use soil production function similar to those proposed by Heimsath *et al.* (1997).

Even if principles of soil evolution over space and time are acquired, less modelling was done to simulate soil evolution over the landscape at fine spatial [1 m] and medium [10 –100 years] temporal scales. Moreover, despite the effort to represent in the existing models the most part of the environmental features e.g. hedges, ditches etc., involved in processes and landscape, some of them have not been yet fully considered.

In the presented study, we propose a model, the LandSoil model, which is an event based model, dimensioned for fine spatial [1 m] and medium [10 –100 years] temporal scales, taking into account a detailed representation of the agricultural landscape. The aims of this study is to use pedological knowledge acquired from a field study coupled with the LandSoil model to simulate soil evolution at fine spatial and medium temporal scales. We model water-erosion and mechanical erosion within a landscape, taking into account anthropogenic landscape structures. Subsequently we apply this model to study the effect of different scenarios of land management and climate changes on soil cover and landscape evolution.

Methods

The study area

The field experiment was carried out at Roujan (Languedoc-Roussillon –FRANCE 43°30’N – 3°19’E). The Roujan watershed unit of 91 ha is located in the south of France (Hérault, France), submitted to a sub-wet Mediterranean climate type characterized by a long dry season (P = 650 mm/y; PET = 1090 mm/y). Its first justification is to allow the study of global changes affecting hydrosystems in agro-systems located in Mediterranean context. The Mediterranean context is well adapted to study the system vulnerability to anthropic and climatic changes. Mediterranean climate is characterized by hydrological constraints (flooding, droughts, water erosion) having a strong impact on the evolution of soils. Land use is almost exclusively vineyards but may drastically change over years.

Data collection

A geological and a pedological map (1/25 000) on the watershed were established by Coulouma *et al.* (2008). We decided to increase the pedological database with data collected during two pedological survey on the wathershed. First, we implemented a 25 m square sampling scheme and described the soil profiles to assess the general soil organization over the landscape. To take into account the short-distance variability of soil geometry in the vicinity of landscape structures, we added soil profile description in their neighborhood. The topography of the area has been surveyed by a LiDAR system and is represented by the derived digital elevation model with [1m] of spatial resolution. The use of area is characterized mainly by vineyard, cereals, and some scrubland/wildlands. The spatial field structure is described by parcels with a medium size of 0.4 ha. An analysis of historical documents was performed to determine the age of hedges and ditched structures. This was done by comparing historical documents: the land registry from the year 1833, called "Napoleonic registries"; aerial photographs from 1946 to 2009.

The Model

The proposed *LandSoil model* (Landscape model for soil conservation under land use and climate change) is an expert-system based on a raster distributed-approach. It is, in fact, an evolution of the STREAM soil erosion model (Souchère *et al.* 1998; Cerdan *et al.* 2001) and new functions and modules are introduced in order to evaluate more soil and landscape specific characteristics. The model has been developed in order to characterize the dominant surface processes leading to overland flow in relation to soil surface properties following laboratory and field researches carried out in France (e.g. Fox and Le Bissonnais 1998; Le Bissonnais *et al.* 1998). Runoff and soil erosion reference data have also been collected in a variety of weather conditions, land use and soil surface state.

The model is rainfall event based and runoff and infiltration are evaluated at every event starting from the characteristics of the rain and the soil surface. It is composed of three modules for soil erosion/redistribution: rill erosion (Souchère *et al.* 2003); interrill erosion (Cerdan *et al.* 2002); and tillage erosion based on the mechanistic rules developed by Govers *et al.* 1994. Soil deposition is accounted by two modules (rill and interrill) following the rules of the local maximum transport capacity. After each rain and tillage event a new topography is evaluated as well as all the geometric landscape parameters. For a more detailed characterisation of the soil surface conditions, a monthly input parameterisation of the properties has been implemented and the rules concerning the soil susceptibility to erosion have been defined for all the main soil types of the area.

Specificities of the model are: i) long-term landscape analysis and topography balance after each rainfall; ii) evaluation of water erosion and soil mechanistic redistribution (tillage erosion); iii) taking in consideration of the landscape geometry, especially the connectivity, as a significant information in describing the landscape and useful in modelling (Landscape structure management and landscape design); and iv) utilisation of various and different climate scenarios thanks to the event based model.

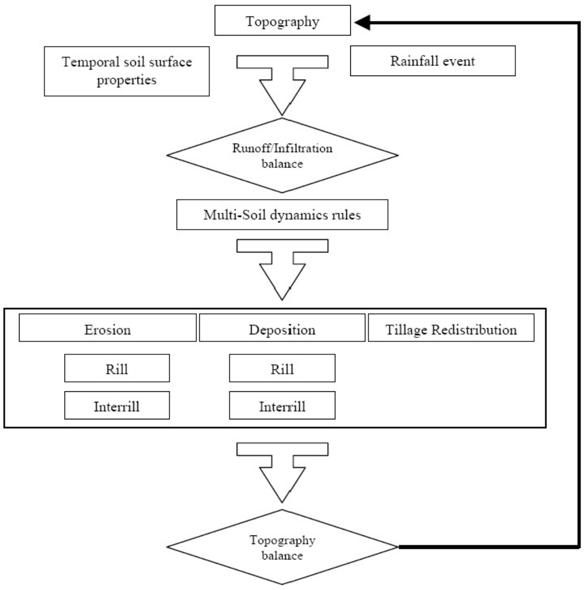

Figure 1. LandSoil module scheme.

Results and conclusion

The model has been calibrated and validated under the current environmental conditions and landscape structure. It has been observed a significant contribution in soil conservation by the landscape geometry even in short term simulations. The simulated soil depth evolution, compared with the present soil cover detailed by the surveying, confirm the observed patterns in terms of soil development and redistribution. Land use, cultural practices and agricultural landscape structure are also able to directly influence sediment fluxes, then the related topographic evolution.

Starting from the analysis of historical rainfall series, different climate scenarios have been tested in order to understand and analyse the resulting effects. The present landscape structure, tested under the perspective of climate changing showed a mitigating effect in terms of soil erosion confirming the importance of a detailed representation of the system geometry. This modelling constitutes a first approach to integrate over time the complexity in soil-landscape evolution. Further improvements should integrate the results of dating techniques (137Cs, 14C) to adjust for the process dynamics. And future developments will manage soil organic carbon redistribution and dynamic over the landscape.

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Modelling soil formation along a loess toposequence

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Abstract
The Soilgen model now includes mechanistic and functional descriptions of soil forming processes such as physical and chemical weathering, organic matter turnover, migration of soluble salts and clay, bioturbation and erosion/sedimentation. With these processes, it is in principal possible to simulate the formation of Ah, E and Bt horizons at the pedon scale using the CLORP factors as exogenous inputs. The sensitivity of the model with respect to these factors was tested, and the model was applied on a toposequence in the Belgian loess belt to evaluate if differences in soil properties occuring as a result of slope angle and exposition with reference to prevailing rain-carrying winds could be reproduced. Results indicate that this is possible after calibration of the calcite dissolution constant and parameters affecting clay dispersion and transport. Additionally it is concluded that calibration protocols need to be developed that can deal with the situation that only the current state of the soil profile is known, the simulation model contains many parameters and runtimes are high.

Key Words
Modelling, pedogenesis, toposequence.

Introduction
Modelling of soil genesis is useful because it provides a deterministic temporal interpolator of soil status for the most common circumstance that only the current state can be measured and evidence of earlier situations is scarce or absent. Thus it can be used in soilscape reconstructions (e.g. for archaeological or palaeoclimatological research), but also to assess future soil behavior at pedogenetic timescales under scenarios of climatic change, and to explain observed soil diversity. Few models exist that are able to simulate changes in time of depth profiles of various soil characteristics, and most soil models focus on some aspects of soil development only (C-sequestration, chemical weathering and acidification processes and filtering and buffering functions) with little focus on long temporal extents. An early example on the pedon-scale was the Century model (Parton *et al*., 1987) for the biogeochemistry of carbon, nitrogen, phosphorus, and sulphur. Recently Finke and Hutson (2008) developed the SoilGen1 model describing various aspects of soil genesis in calcareous loess. The latter model has been successfully applied to evaluate differences in soil development as a function of climate evolution. It would be interesting if this model would also be able to explain soil diversity within one climate. For this reason the model was applied to a toposequence in the Belgian loess.

Methods
Soilgen model
Figure 1 gives a schematic overview of the processes simulated by Soilgen. Depending on the process dynamics, timesteps vary from minutes-hours (water, heat and solute flow), days (plant growth and OM dynamics, weathering) to one year (bioturbation, plowing, fertilization, erosion, sedimentation). The transport routines were taken from the mechanistic LEACHN-model (Hutson, 2003), and the OM turnover was modelled according to the descriptions of the functional RothC26.3 model (Coleman and Jenkinson, 2005). Recently, the processes of clay migration and weathering were added to the model. Clay migration is initiated at the surface by splash detachment. If the clay remains in dispersion and can be transported depends on ionic strength which is mimicked with soil pH and on filtering. Transport of the dispersed clay fraction is modelled like solute transport but with particle filtering as an additional sink term. Physical weathering is modelled as a probabilistic process, where the splitting probability of a particle depends on the temperature gradient over time. Chemical weathering is modelled as a first order degradation of minerals.

Loess toposequence
In central Belgium, a forest remains that has been used for hunting ground and timber production, but was probably never under agriculture, as documents from the 13th century onwards prove. The relief in this forest probably hardly changed since the deposition of the loess cover (of about 4 m constant thickness) on a

dissected landscape in tertiary marine deposits. A toposequence of a soil on a plateau position, on a SW facing slope and on a NE facing slope were sampled and described in detail (Van Ranst, 1981). The genesis of these profiles was simulated with the Soilgen2 model. The same climate evolution of 15000 years was applied as boundary condition, but as expositions and slope angles varied, so did net precipitation entering the soil. For this reason, decalcification depth at the plateau position and SW-facing slope is 3.50 m and more because of the higher exposition to the SW wind which brings most rain, while on the NE facing slope it is about 2 m. Also, the Bt-horizons were observed to be more pronounced at the plateau and SW-facing slope. These 2 soils were classified as stagnic albic cutanic Alisol (fragic, alumic, hyperdystric, siltic), while the soil on the NE slope was classified as cutanic lamellic Alisol (alumic, siltic).

Environmental factor		Link to model	Modeled processes: SoilGen1 (Finke&Hutson 2008)	SoilGen2
CLimate	Temperature	BC	Heat flow	
	Precipitation: water	BC	Water flow	
	Precipitation: solutes	BC	Solute flow	
	Evaporation	BC	Evapotranspiration	
Organisms	Vegetation	BC	C-cycle	
		SIM	CO_2-production and diffusion	
		SIM	Selective cation uptake/release	
		BC	Root distribution	
	Fauna	BC	Bioturbation (as input)	
	Human influence	BC	Fertilization	+ Plowing
Relief	Slope	IC	Runoff	
	Erosion / sedimentation	BC		Input as events
	Variants of T, P, E	BC's	Heat/water/solute flow	+ P, E =f(exposition)
Parent material	Texture	IC+SIM	Chemical Diss./prec, bioturbation, C-cycling	+ Physical weathering + Clay migration
	Mineralogy	IC	Cation exchange	+ Weathering primary minerls
	Species of Ca, Al, Mg, K, Na	IC+SIM	Chemical equilibria	
Time	Change of all BC's	BC	Annual update of all BC's	

Figure 1. Processes simulated in Soilgen and linkage to the CLORP factors via BC or IC (Boundary or Initial Conditions, forcings) or simulation (SIM).

Calibration

The soilgen model was calibrated by adjusting the calcite dissolution equilibrium concentration until the depth of decalcification for a high precipitation surplus (472 mm/y) simulated by the model was equal to that of a metamodel by Egli and Fitze (2001) based on pan-European soil data. Thereafter, results were compared with data from this metamodel for lower precipitation surpluses. Clay migration was calibrated by adjusting a filtering coefficient so that the zone of clay accumulation appeared at a realistic depth in the soil. Faulty values lead to loss of clay from the entire profile or no clay migration at all.

Results and discussion

The comparison after calibration of calcite dissolution constant resulted in comparable times-to-decalcification at other precipitation surpluses (Figure 2) all though decalcification speed with Soilgen is slightly slower in dryer climates than with the metamodel. After calibration towards the appearance of a clay illuviation of the soil, the 3 profiles of the toposequence showed a marked difference in depth of decalcification and the distinctness of the development of an E and Bt horizon (Figure 3). At the SW-facing slope and the plateau, decalcification (shown by pH) is deep and a clear E and Bt develop. At the NE facing slope, decalcification is close to 200 cm, a clear E develops but the Bt is much less marked. This is in accordance with field observations, all though the whole profile lost clay in the simulations which is probably not realistic. Also (not shown, but see Finke and Hutson, 2008) the development of an Ah horizon was reproduced by the model. Simulation time was substantial, and calibration of the clay migration part done on a qualitative rather than a quantative basis.

Conclusion

Observed differences in soil formation on a toposequence could be reproduced by the soilgen2 model, and the presence of Ah, E, Bt and Ck horizons was simulated as well. Efficient calibration methods need to be developed for the situation that only current state measurements are available and simulation time is long.

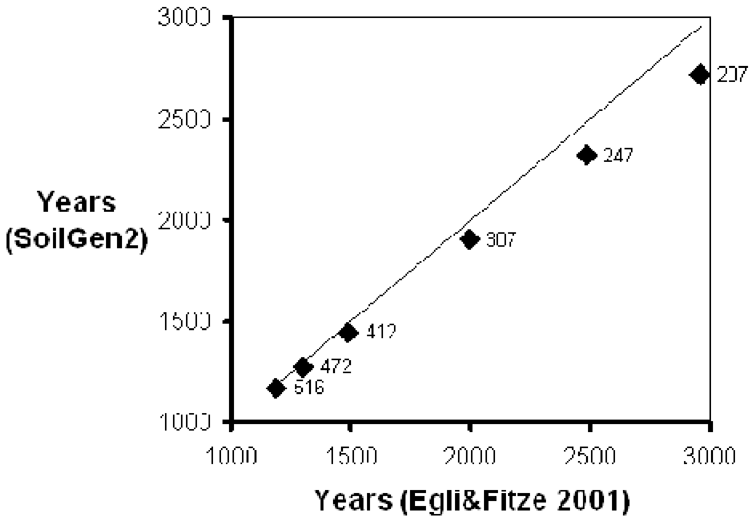

Figure 2. Comparison after calibration of time-to-decalcification of 1100 mm of soil with SoilGen2 and the Egli and Fitze (2001) metamodel. Numbers indicate precipitation surpluses.

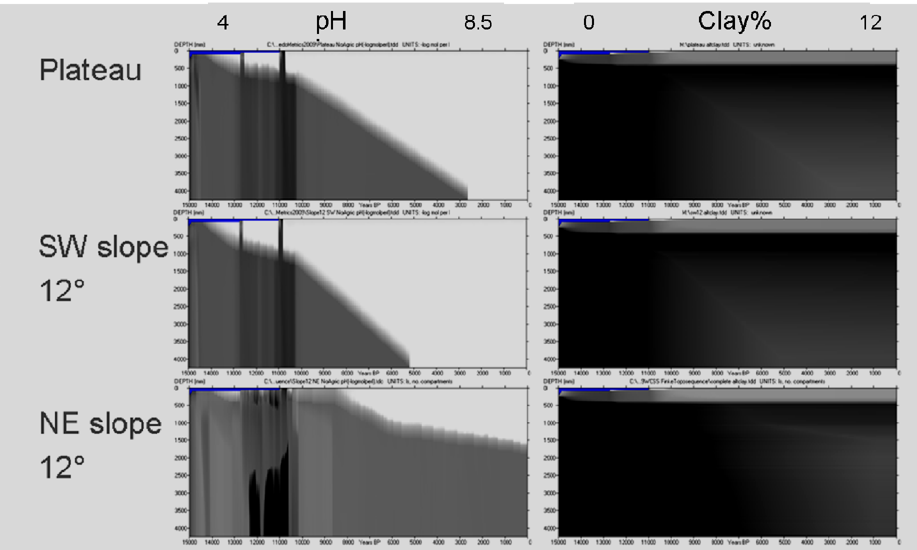

Figure 3. Time-depth diagrams for 3 profiles in the toposequence for pH and clay content with Soilgen2.

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Soil reactions to extreme environmental stress: lessons from the past records

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Abstract
Two paleosol sequences of the Late (South France) and Middle Pleistocene (South China) were investigated using a high resolution approach associated with SEM-EDS and XRD analysis on selected grains. This approach has enabled us to distinguish the repetitive succession of an initial pedogenic phase, ending by a soil disruption in response to an abrupt event. In South France, the sequence is terminated by a cryogenic episode associated with poor drainage as indicated by the hydromorphic characters that are superimposed on the earlier pedogenic events. In South China, the disruption episode is associated with the presence of macro and micro-tektites which leads to interpret this disruption as due to a cosmic airburst. The clear signatures of exceptional events in these Pleistocene paleosols have at present no analogue in modern soils. Their considerable high amplitude in comparison to the gentle stress that is generated by the global warming suggests that paleosols are of limited use for predicting effects on soils of the ongoing atmospheric change.

Key Words
Hierarchy of features, pedo-sedimentary sequences, extreme events, uniformitarism refutation.

Introduction
Intense research effort on high resolution marine, ice, lacustrine and loess sequences has considerably changed our perception of the Earth recent history. By combining a suite of multi-proxies, interdisciplinary studies have identified the occurrence throughout the last glacial cycle, as well as during the Holocene , and most probably during the former glacial and interglacial cycles, of recurrent abrupt climate forcing with centennial, even decennial, time-scale variability (Alley *et al.* 2003, Alley and Ágústsdóttir 2005). These cyclical and rapid climatic changes, known as the Dansgaard-Oeschger cycles, Heinrich events, or the Younger Dryas for the last glacial period, are now well established to have been global however with variable regional expressions depending on local settings (Broecker 1994). Stormy crisis preceding the initiation of loess deposition have took place within short periods (Rousseau *et al.* 2002). Surprisingly, the signatures of these short climate crises have not drawn much interest in paleopedology. The research conducted on paleosols have not seriously revisited the principles of linearity and of uniformitarism applied to soil development. Gaps in soils are still suggested to reflect thresholds independently from external factors.

However already in 1956, Erhart distinguished periods of stability favourable to soil development (biostasy) alternating with episodes of instability marked by soil erosion (rhexistasy). Haesaerts and Mestdagh (2000) have precisely deciphered in paleosols the succession of glacial/interglacial episodes stages that have developed through Europe during OIS 5. Porter and An (1995) have easily identified the signal of Heinrich events in the Chinese loess deposited during glacial periods, while Courty and Vallverdu (2001) identified the soil features resulting of abrupt events in exokarstic cavities of the Western Mediterranean region which trapped the soil cover extensively eroded during these exceptional crises. Similarly, Courty *et al.* (2008) have identified in various regions the widespread disruption of soil-landscapes at 4 kyr BP in response to extreme conditions. Our aim is at first to illustrate the record in paleosols and soils of abrupt events based on two key-studies. Then arguing for the irrelevance to apply the principle of uniformitarism to paleosols, we question the real potential of soil archives for predicting the effects of the global warming on soil development.

Methodological approach and key-studies
The methodology that we have developed (Courty *et al.* 2008) is aimed to provide a precise estimate of the integrity of the soil record with respect to its paleoenvironmental relevance. We combine the survey of serial trenches that provide sequences of paleosols and intercalated sediments across landscape units with the detailed investigation with of linked assemblages of artefacts, bones and rock clasts. This approach allows to

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view the developmental stages of paleosols within the general frame of landscape evolution. The well preserved paleosurfaces, provide access to distinctive events along the course of this historical frame. Laboratory analysis are at first performed on test samples obtained from strategic positions. Micromorphological study of a few thin sections are combined to SEM-EDS and XRD analysis on distinctive components picked up by hand under the binocular microscope after extraction from the soil matrix by water-sieving. Results from the tests help to select the best preserved records for performing a complete analytical characterization by adjusting high resolution sampling to the set of pedo-sedimentary entities deciphered in the field. Samples for absolute dating are collected from controlled situations. The interpretative phase consists of the following stages: (i) identification of the pedological and sedimentary features; (ii) establishment of a chronostratigraphical frame giving the successive pedological phases and sedimentary episodes on the basis of hierarchies between all the identified features; (iii) exploration of the genetic linkages between the host soil matrix and the included elements, e.g. human artefacts or allogenic components linked to cosmic (i.e. tektite) or volcanic (i.e. tephra) events. A great attention is given to distinguish *in situ* formed soils, disturbed, but still in situ soils, transported soil materials (pedo-sediments), and true sediments that are not affected by pedogenesis.

The first key-study is located in southern western France at the transition of the Landes to the Chalosse regions near Saint-Gein. The sections are on a water divide. The surface soil, a Gleyic podzol, is developed in Late Pleistocene sands that are overlying a sequence of superimposed paleosols consisting of truncated Glossalbic Luvisols. The upper argic horizon is yellowish brown whereas the lower one is dark red. The lower yellowish brown argic horizon is locally strongly impregnated by manganese oxides. The dark red argic horizon lies over Tortonian clays which present the morphology of a reworked, bright red, aquic argic horizon. Abundant Mousterian artefacts are embedded in the matrix of the upper yellowish brown argic horizon. This sequence was compared at first to a younger sequence of paleosols situated nearby at Pujo-le-Plan in which Mesolithic artefacts are present at the base of the Landes sands just above the glossic soil. The second sequence used for comparison is also located near-by on a high terrace of Adour near the village of Cazères-sur-Adour. Acheulean industry was found in the upper yellowish brown argic horizon. The present day climate of the area is mild and humid with 990 mm of annual precipitation.

The second key study is located in the Bose basin in Guangxi province (south China) where the present-day climate is of tropical monsoonal type. The investigated paleosol sequence is developed on the fourth terrace (T4) of the Younjiang river. Six meters of Cumuli Gleyic Acrisols are sandwiched between cobble conglomerate and a recent soil cover (Qiuzhen and Guo 2006). Extensive excavation have demonstrated the association over several tens of kilometre of *in situ* tektites with delicate forms together with Acheulean-like stone tools and charcoal fragments in the T4 paleosol unit (Yamei *et al* 2000). The 803 $\pm$ 3 ka ^{40}Ar/^{30}Ar age of tektites is in agreement with their attribution to the Australasian strewnfield assumed to represent the dispersion area of melted by-products from a major cosmic impact (Lee and Wei 2000).

Results

At Saint-Gein, the argic ground masses viewed at microscopic scales consist of an undifferentiated mass that contain deformed and fragmented clay coatings and infillings while some voids are coated by a new set of clay coatings and infillings. The glosses are depleted iron oxides while in the centre voids are infilled by poorly sorted, bleached clays in the form of intercalations. A hierarchy between glosses has been recognised. In the Saint-Gein area, in each paleosol the following stages have be recognized: (i) a phase of clay illuviation corresponding to a period of stability (a biostasy phase), (ii) an episode of soil disruption characterized by deformation and fragmentation of illuviated features, however the distribution of human artefacts is preserved to a large extent which means a severe but *in-situ* disruption, (iii) formation of an hexagonal network of ice wedges, (iv) replacement of ice wedges by a slow migration of reduced water enriched with iron oxide depleted clays, (v) sediment accretion. We assume that the stage of severe soil disruption corresponds to an abrupt event, probably an airburst. It was followed by a cold episode responsible for the ice-wedges. The soil disruption destroyed most of the existing porosity making the disrupted argic horizon impermeable which induced during the next period of stability seasonal waterlogging (water could circulate only in ice wedges). A new cycle starts with an accretion of glacial sediments.

In Bose, the 6 m thick Cumuli Gleyic Acrisol does not display any horizonation, although a polyphased organisation is observed at microscopic scales. In the layer containing tektites the organisation is the following: (i) a reddish, disrupted, ground mass, in which fragments of clay coating and charcoal micro-fragments can be distinguished, (ii) irregular bleached zones, (iii) compound coatings showing an irregular alternation of microlaminated clays, dark fine silt layers and infillings generally located in the bleached zones. SEM-EDS and XRD analysis on discrete components revealed the presence of: (i) tektites micro-fragments, (ii) clasts of marine mud with foraminifera and radiolarian, (iii) clusters of aliphatic polymers, (iv) angular quartz, translucent glass shards, actinolite and zircon grains, (v) droplet coating on sand grains formed of native metals (iron, chromium, nickel, copper and zinc). The following stages of development can be proposed for the tektite layer: (i) an episode of soil disruption characterised by fragments of clay coatings synchronous to the incorporation of allogenic components, (ii) seasonal waterlogging characterized by bleached zones, a consequence of soil disruption, (iii) a phase of irregular illuviation.

Discussion and conclusion

The disruption of the soil fabric appears as the most striking character resulting from extreme events. The two key-studies illustrate the in situ disruption of the soil components, although lateral displacement in the form of a mud flow is also possible. In Bose (China), the occurrence of macro and microtektites in the disrupted soil matrix provides strong evidence for relating the disruption phase to a surface airburst in relation with a cosmic event. The subsequent waterlogging suggests an immediate rainfall increase. Our first case study shows an excellent record of periodical extreme events in a paleosol sequences that can be paralleled to the ones usually identified in ice, ocean and lake floors. Soils are the most accurate recipient with ice of extreme events because they are directly exposed to atmospheric changes and thus concentrate space debris, just simply filtered by the atmosphere. Refined investigation in the future on the periodicity of these extreme manifestations, specifically on the loess/paleosol sequence of the Loess Plateau of China, should greatly help to further elucidate their exact role on atmospheric perturbations and the linked environmental changes. Their identification emphasizes the discontinuous dimension of soil development through time that contrasts from the long accepted view of steady and gradual soil evolution.

The lack of an appropriate field-analytical methodology for detecting the unequivocal fingerprints of extreme events explain why paleopedology has been for so long mislead by the concept of uniformity (Gould 1987). A more dynamic perspective of soil development can be achieved by decoupling the genesis of paleosols into a succession of phases and cycles by applying the concept of the hierarchy of features (Fedoroff and Courty 2002). This approach incites to distinguish four types of paleosols:

1. The cyclical paleosols that display a paleosol and the overlying sediment. The rapid accretion of sediments (most frequently loess) as the result of an extreme event lead to complete burial of the paleosol. The sequence can be monophased, bi or triphased, as well illustrated by the Chinese loess/paleosol record.
2. The accretion of sediments was not sufficient to instantaneously bury the paleosol as illustrated by the St-Gein paleosol. Two and more phases of pedogenesis, e.g. clay illuviation, are overlapping and separated by unconformities.
3.The paleosol that appears in the field as an undifferentiated paleosol complex shows under microscope pedogenic features that are typical of extreme events as in the case of Bose; however their intense disruption at the time of formation has partly erased the soil record of short-term cyclicity.
4. The paleosol that is in general a relict soil, e.g. ferralsols, in which the presently available tools do not permit to identify in the field and also in laboratory, any hierarchy of features.

Although the triggering processes yet remain to be further elucidated, the recent recognition in paleosols of evidences linked to extreme events once more emphasizes how conceptual models progress from stimulating objectives.The assumption that paleosols can be used for predicting the future soil evolution due to the predicted global warming is questionable. The progressive temperature elevation of the modern area is weak in contrast to the nearly instantaneous drastic temperature changes of the past, up to 10°c in a few years, e.g. at the Younger Dryas. Furthermore, the subtle effects of the atmospheric changes linked to industrial activities are not accompanied by the range of severe manifestations that occurred in the past at the time of extreme events, i.e. airburst, extended wildfires. Moreover, the predominant effect of human impact on present day soils makes comparison with soils of the past more difficult. Soil characteristics resulting of soil biological activity and organic matter evolution can be used as references for the future when considering Holocene soils. These characteristics have however to be handled with great care because past faunal activity is estimated only by excrements and eventual preserved animal remnants, while the soil organic matter, even in buried soils, is ageing rapidly. Exchangeable cations (Pal *et al*. 2009) and soluble salts (Hamdi-Aissa, 2004) might be good indicators for tracing the evolution in soils of the recent past simply because of their high reactivity to the soil water regime.

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Shale weathering rates across a continental-scale climosequence

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Abstract
A transect of sites has been established in North America as a Critical Zone Exploration Network (CZEN) to investigate the rates of soil formation across a climate gradient. Sites reported here are all underlain by an organic-poor, iron-rich Silurian-age shale, providing a constant parent material lithology from which soil is forming. This climosequence includes relatively cold and wet sites in Wales, New York and Pennsylvania, with temperature increasing to the south in Virginia, Tennessee and Alabama. Puerto Rico provides a warm/wet end member for the transect, although this site does not lie on the same shale formation as the Appalachian Mountain sites. Data, including geochemistry and mineralogy, will be measured similarly at all sites to allow direct comparisons and eventual modelling of the weathering processes. Preliminary results from Wales, Pennsylvania and Virginia show sodium depletion with depth, with the depth to bedrock significantly deeper at the wet/warm site in Virginia. The fraction of Na lost relative to parent material composition at each site varies linearly as a function of mean annual temperature. Overall, results from the transect will promote a better understanding not only of how climate is influencing soil production, but also the role of human impacts on soil formation rates.

Key Words
Soil, weathering, climate, shale.

Introduction
Terrestrial life is wholly dependent on the properties and processes within the critical zone, which encompasses the top of the tree canopy to aquifers beneath the earth's surface (Brantley *et al.* 2007). As the central constituent of this zone, soil serves as an interface for gas and water exchange and plays a major role in nutrient cycling that supports ecosystems (Amundson *et al.* 2007). However, the rate at which soil forms in the critical zone is not well understood. In working to address this question, numerous researchers have looked at how soils differ in form and function across environmental gradients. These studies have included quantifying physical erosion, pedogenic development, and geochemical fluxes as a function of climate and various parent materials (i.e. Rinaido *et al.* 1995; Chadwick *et al.* 1990; White and Blum 1995; White *et al.* 1999; Rasmussen *et al.* 2007; Jin *et al.* 2009). While these studies have included both field and laboratory measurements of chemical and physical weathering rates, they have focused on small-scale climo- or chronosequences, such as Hawaii or the Pacific Northwest, and generally only address one mineral or system component; scaling-up these results to understand more global processes is problematic. Additionally, literature synthesis studies, such as that by Bockheim (1980), have used previously published data to investigate the influence of gradients on soil properties, but not all data was collected in the same manner, complicating interpretation. There is a need, therefore, to understand weathering rates at a larger scale and to integrate geomorphology, pedology and geochemistry to interpret complex soil systems. A Critical Zone Exploration Network (CZEN), in which sites and scientists are linked across environmental gradients, is being developed to investigate rates of soil formation. Here, we report rates of soil formation on shale as a function of climate (Figure 1).
The conceptual framework of the CZEN sites is not unlike the soil formation model proposed by Jenny (1941) in which the type of soil formed at any given location varies as a function of climate, organisms, relief, parent material and time. When research sites are chosen based on manipulating one variable while holding the others relatively constant, processes, such as rock weathering, can be more effectively quantified. The approach of investigating large-scale environmental gradients has already been successfully employed in investigating the dissolution of feldspar in loess parent material along the Mississippi River in the United States (Williams *et al.* 2009). In much the same vein, the CZEN outlined here will test the hypothesis that shale weathering rates vary predictably as a function of climate.

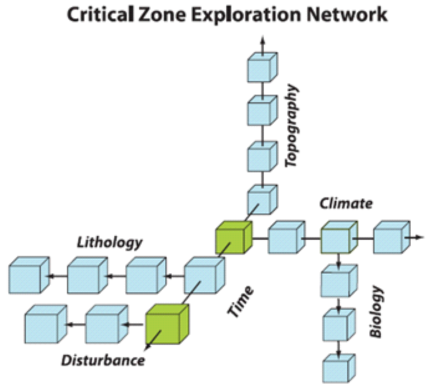

Figure 1. Conceptual diagram for the Critical Zone Exploration Network (CZEN) used to test environmental gradients. Figure from Brantley *et al.* (2007).

Methods

Site selection

The climosequence is defined by the following seven sites: Wales, New York, Pennsylvania, Virginia, Tennessee, Alabama and Puerto Rico (Figure 2). Wales provides a cold/wet end member of the transect and Puerto Rico represents a warm/wet end member. Sites are located on the same Silurian-age, Fe-rich, organic poor shale, with the exception of Puerto Rico, which is located on a chemically similar, but younger, shale. To identify sites, GIS was used to isolate similar locations with respect to lithology, aspect, topography and land use. After locating potential sites, field work at each site confirmed similarities. Furthermore, all sites were located on "1-D" profiles, along ridgetop topographic positions, to represent the simplest model of soil-rock interaction (Jin *et al.* 2009). In a "1-D" profile water enters the top of the profile and proceeds vertically to bedrock, at which point lateral flow may occur; this simple model facilitates comparison across sites (Brantley and White 2009). Also, stratigraphy was considered to ensure similar sampling locations within the shale unit (Giri 2008). Finally, attempts were made to minimize the contributions from glacial till and colluviums as much as possible. Variables which varied unavoidably among sites included vegetation and exposure age. An implicit hypothesis underlying our study is therefore that the effects of these variables on rates of soil formation are minor compared to climate.

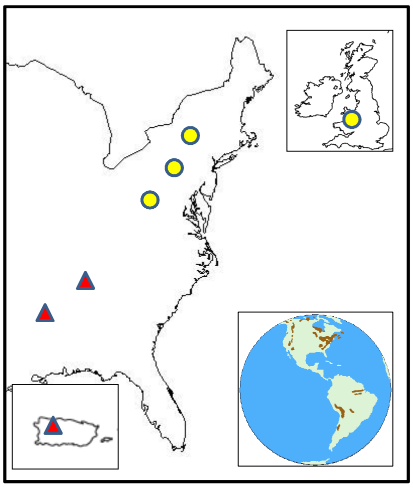

Figure 2. Sample site locations on the climosequence. Circles represent sites already sampled while triangles represent future sampling sites. Lower left inset shows Puerto Rico, upper inset shows Wales (Plynlimon watershed) and inset globe shows distribution of Silurian-age shales in the western hemisphere.

Soil sampling and chemistry

Soils at each site were sampled by depth (10 cm increments) using a 5 cm diameter auger. Bedrock depth was defined as depth to refusal. Bulk soil chemistry was measured by grinding soils with a mortar and pestle to pass through a 100 mesh sieve (150 μm). A Li metaborate digestion followed by inductively coupled plasma atomic adsorption spectroscopy (ICP-AES) determined major elemental oxides (Medlin *et al.* 1969). To quantify the relative mass of elements lost from the parent rock, the dimensionless coefficient τ was calculated, with a value < 1 indicating depletion of an element relative to unweathered bedrock and a value > 1

showing enrichment relative to bedrock (Brimhall and Dietrich 1987; Chadwick *et al.* 1990). For these calculations, titanium was used as the immobile element and parent was defined as the average of multiple bedrock samples collected at each location. Error was propagated from analytical error plus the standard deviation of parent compositions for multiple shale analyses on samples collected near the auger sites.

Results

Presented here are preliminary results from sites in Wales, Pennsylvania (PA) and Virginia (VA). Depth to bedrock is nearly identical in Wales and Pennsylvania (35 cm and 30 cm, respectively) while depth to bedrock in Virginia is 100 cm. Sodium, which is inferred from detailed mineralogy at the PA site to be present as feldspar, shows depletion profiles at all three sites that vary in extent with location (Figure 3) (Jin *et al.* 2009). In Wales and PA, approximately 20% depletion of Na is observed at land surface, whereas almost 50% depletion relative to parent composition is observed in VA. The bottommost sample for all three profiles, however, does not return to the average parent composition for that site, suggesting that the depth to unweathered rock is significantly deeper than the bottom of the augered profile.

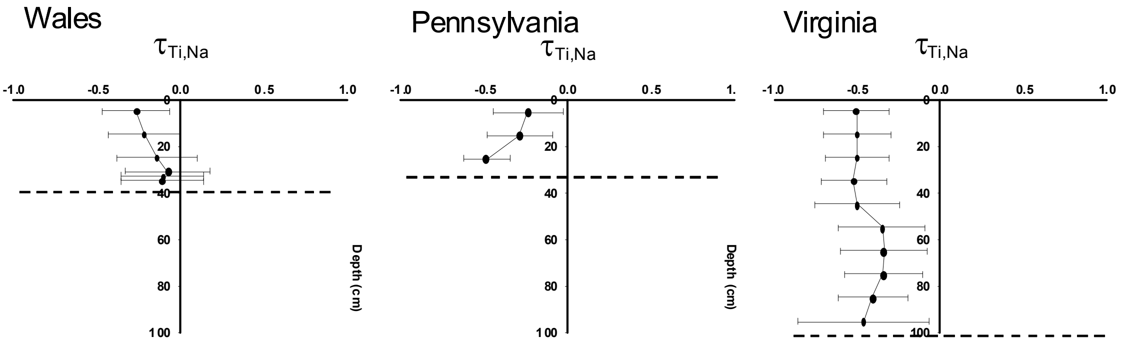

Figure 3. τ values for Na as a function of depth in Wales, Pennsylvania and Virginia. Dotted lines represent depth to bedrock at each site.

The fraction of Na depleted relative to the average parent composition varies as a function of both mean annual temperature (MAT) and mean annual precipitation (MAP). The total fraction of Na depleted from the entire augered profile increases linearly with MAT, from only 20% Na lost at the coldest site in Wales to almost 50% at the warmest site in VA. In contrast, the fraction of Na lost as a function of MAP increases from PA to VA but decreases in Wales. While the site in Wales receives 1.6 to 2.5 times more precipitation than VA or PA, the fact that soils are the least depleted in Na in Wales documents the strong role of temperature in controlling weathering of feldspar.

Conclusion

Preliminary data from a large-scale climosequence suggests soil chemistry and depth to bedrock vary with changes in temperature and precipitation. Na has been depleted in all profiles examined thus far, with more depletion relative to bedrock at the warmest site. In the colder, wetter sites, only 20% of Na has been weathered from the soil profile while the warmer, wet VA site has lost 44% of Na compared to original parent. Na depletion varies monotonically with temperature but not with precipitation. Although data are preliminary, the climosequence approach to addressing the question of shale weathering rates shows potential for quantifying weathering processes in soils underlain by the same lithology. The approach outlined here will also be used to investigate other environmental variables. For example, lithologic contrasts will be analysed between the organic-poor shale reported here and another site located on organic-rich shale, also in PA. Also, land use contrasts can be compared in Wales, where two catchments, roughly identical in size and lithology, are managed as grassland and forest – these sites can therefore provide insight on the effects of land use on shale weathering. Finally, this climosequence could eventually be extended to an equator-to-pole gradient study of Silurian-age shale soils extending from West Africa to Spain, Wales, Norway and Svalbard.

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Rates and variability of hillslope erosion in steepland catchments in the Oregon Coast Range, Pacific Northwest, USA

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Abstract
Hillslope soil residence time (average particle age making up the soil) reflects the rates of soil production (= bedrock erosion) and soil transport, and thus is a useful parameter for quantifying hillslope dynamics. On steady state hillslopes, the distribution of particle ages is determined by soil production rate, soil depth and soil and bedrock density. This distribution, used in combination with chronofunctions describing soil weathering at a particle scale, can be used to derive expressions relating hillslope soil properties to soil residence time. Thus soil properties can be used to estimate soil residence time and quantify hillslope dynamics. We analysed variability of soil residence time at a broad scale and a fine scale in the Oregon Coast Range in the Pacific Northwest, USA. Our results are consistent with an approximate balance of erosion rate and rock uplift rate for a large part of our study area, but at both scales, parts of the landscape with long soil residence time were identified. We attribute the lower erosion rates and slower soil transport (contributing to long soil residence time) in these areas to decoupling from base-level lowering.

Key Words
Soil residence time, soil chronosequences, chronofunctions, soil production.

Introduction
The use of soils as a surface exposure dating technique is well established. Typically, numerical ages are calculated from empirical chronofunctions calibrated locally from soil chronosequences, and soil properties from a surface of unknown age. Dating relies on a number of assumptions including: 1) monotonically increasing expression of soil development with increasing soil age, 2) rates and pathways of soil evolution have remained constant in space and time over the study area, 3) the manifestation of soil age in the chronosequence is the same as on the landforms for which an exposure age is to be determined. The last is usually assured by dating soils with similar soil forming factors to the calibration data set. For example, a chronofunction calibrated from soils on a flight of terraces should not be used to derive an exposure age for an eroding soil-mantled hillslope. In this case the factor of relief is different. More fundamentally, the distinction between these two situations, which confounds the application of soil surface exposure dating, lies in the fact that the population of grains comprising the soil on a terrace has a singular age (the age of the terrace), whereas the soil on the hillslope comprises a population of grains with a distribution of ages determined by the time since each grain was released from the substrate by soil production.

On hillslopes the concept of a soil/landsurface age is meaningless, but one can refer to the mean soil grain age, or *residence time* of the soil. The extent of chemical weathering of the bulk soil is the integration of weathering of individual grains of different age. But because chemical weathering and other pedological processes generally follow non-linear chronofunctions, there is not a simple correspondence (in terms of soil development) between soil residence time and soil age as defined in the non-eroding soil situation. In this paper we develop a conceptual framework which allows us to use a chronofunction, calibrated from a soil chronosequence on fluvial terraces, to calculate the residence time of hillslope soils from bulk soil weathering characteristics. We then interpret soil residence times in terms of landscape dynamics and the history of forcing of hillslope erosion.

Conceptual framework
For a steady state soil-mantled hillslope, where the rate of erosion is balanced by soil production, it can be shown that the residence time, $\tau = h\rho_s/E\rho_r$, where h is the soil depth, ρ_s and ρ_r are the densities of soil and rock, respectively, and E is the erosion rate (= soil production rate). The soil has a population of grain ages with probability density function given by

$$P(t) = \frac{1}{\tau} e^{-\frac{t}{\tau}} \quad \text{(Mudd and Furbish 2006).} \qquad (1)$$

If a chronofunction can be developed for a soil property for which processes can be scaled down to individual grains, then Eqn 1 can be used to integrate the effects of that process over the whole grain population to determine the bulk soil response. Thus, by measuring weathering-related properties of hillslope soils, armed with a suitable chronofunction, and making a steady-state assumption, hillslope erosion rate and the residence time of soils can be determined.

Study area

The Oregon Coast Range (OCR) is a humid, soil-mantled, mountainous landscape in the Pacific Northwest of the USA, largely composed of Eocene Tyee Formation (sand-rich turbidite deposits) that overlie volcanic basement accreted to the North American plate. The topography is steep and highly dissected with relatively uniform ridge and valley terrain (Dietrich and Dunne 1978; Montgomery 2001; Reneau and Dietrich 1991). Typically, soils are thin (~0.4 - 0.7 m) Inceptisols on hilltops and sideslopes, and thicker cumulate Inceptisols (~1 - 2 m) in unchanneled valleys. Both short- (~10 y) and long-term (~5000 y) studies of sediment yield suggest an approximate balance between erosion rate (0.10 - 0.15 mmy^{-1}) (Bierman *et al.* 2001; Heimsath *et al.* 2001; Reneau and Dietrich 1991) and rock uplift (Kelsey *et al.* 1996; Personius 1995), so that the topographic form may be relatively uniform with time (Montgomery 2001; Roering *et al.* 1999). Our soil residence time analysis covers two scales; a broad scale study encompasses the drainage of the Siuslaw River and the dividing range to Long Tom Creek which drains into the Willamette Valley. A finer scale study contrasts soil residence time distributions of the Hoffman-Peterson and the North Fork Smith drainage systems which drain to the lower reaches of the Siuslaw River. The Hoffman-Peterson drainage system (21.6 km^2, average slope = 60%, average relief = 270 m) exhibits regular ridge-valley topography with narrow valley floors. It drains directly into a tidal reach of the Siuslaw River (~20 km from the Pacific Ocean) and is thus tightly coupled to coastal rock uplift. The North Fork Smith drainage (27.8 km^2, average slope = 39%, average relief = 200 m) exhibits less regular ridge-valley topography with broad alluviated valley floors above a 70 m high gabbroic dike-controlled knickpoint (North Fork and Lower Kentucky Falls).

Methods

A soil chronosequence on fluvial terraces of the Siuslaw River was used to calibrate chronofunctions reflecting chemical weathering and formation of pedogenic oxides. The flight of seven terraces spanned approximately 3.5 ky to 1 My, with ages being assigned using calibrated radiocarbon ages for younger terraces and by calculation from terrace elevation and an approximate uplift rate for older terraces. Soils varied from Entisols to Inceptisols to Ultisols with increasing age. One of the most consistent aspects of soil development was increasing redness. For the broad scale study, a chronofunction (units of ky) describing development of Munsell soil hue of the reddest soil horizon, as assessed during field soil description, was calibrated ($Hue\ No. = 1.98 + 10.53\ (1-e^{-0.0067t})$). For the finer scale study, air-dried soil samples from the reddest horizon were crushed, sieved to <2 mm, placed in a petri dish and photographed with a digital camera. RGB data extracted from image analysis software were then converted to Munsell hue using the algorithm of Viscarra Rossel *et al*. (2006), and a second soil hue chronofunction (units of ky) was derived ($Hue\ No. = 22.4t^{-0.061}$).

In order to be able to relate soil development on hillslopes to soil residence time, we integrated the chronofunctions above across the particle age probability density function given by Eqn 1 to yield an expression relating soil hue to residence time. These expressions were then solved for residence time, τ, in ky for the chronofunctions for field soil hue and digital laboratory-measured hue, respectively:

$$\tau = \frac{H - 2.5}{0.0067(10.53 - (H - 2.5))} \qquad \text{2a}$$

$$\tau = \left[\frac{H}{22.4\Gamma(-0.061+1))}\right]^{-\frac{1}{0.061}} \qquad \text{2b}$$

where H = hue number, and Γ is the gamma function.

The pattern of variability of soil residence time at the broad scale was determined using Eqn 2a and a GIS spatial database of soil hue data taken from a relevant soil map. At the fine scale, the variability of soil residence time was determined using Eqn 2b and digital hue values measured from soil samples taken from the reddest horizon of soils along drainage divides within the Hoffman-Peterson and the North Fork Smith drainages.

Results and discussion

The broad scale analysis shows the majority of the study area, west of the drainage divide to the Willamette Valley, to be dominated by soils with residence time of 8 ± 5 ky (Figure 1).

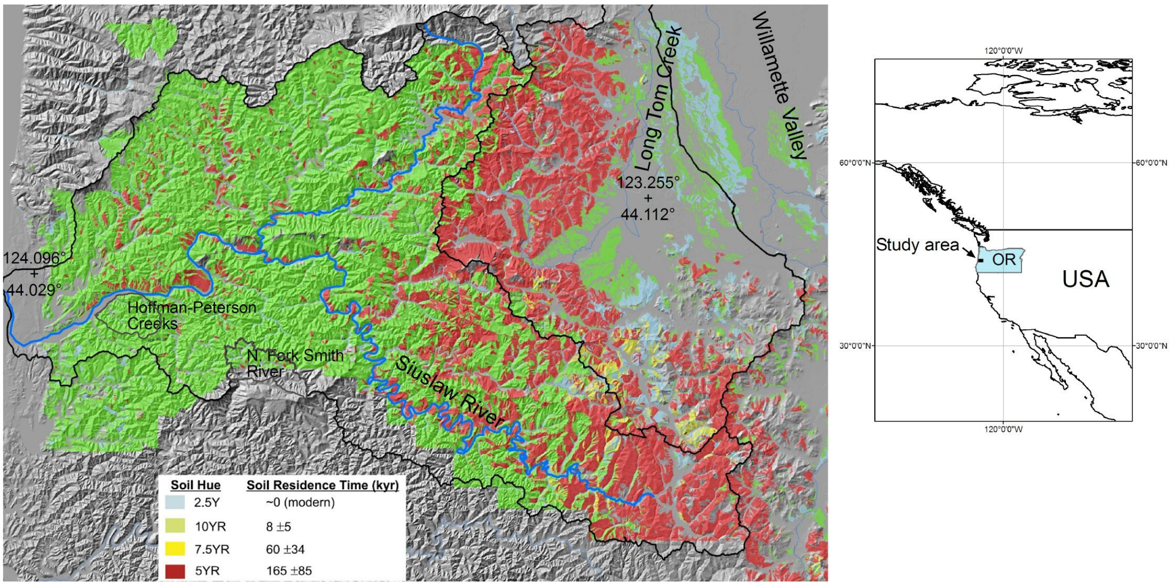

Figure 1. Soil residence times for the study area.

This is consistent with steady state erosion at between 0.10 and 0.15 mmy^{-1} beneath soils with thickness and bulk density typical of the hillslopes of the Coast Range. This part of the study area is well coupled to the Siuslaw River, and it appears that the signal of base-level lowering is being effectively transmitted to hillslopes by processes operating at timescales similar to or less than the soil residence time. Figure 1 also shows inliers of soils of much longer residence time (~165 ky). These areas correspond to river terraces, typically on the inside of migrating meander bends, or deep-seated landslides, which have been temporarily decoupled from base-level lowering owing to their topographic form. Both the landslides and terraces form broad, low-gradient surfaces on which soil transport is minimal, erosion rate is low, and chemical weathering is advanced. The area east of the drainage divide to the Willamette Valley has average soil residence times approaching 150 ky. The long soil residence time probably relates to structurally controlled diversion of east to west flowing streams, formerly contributing to the Siuslaw River system, into the Willamette Valley (Baldwin and Howell 1949). In contrast to the Siuslaw, Long Tom Creek is broad and alluviated and base level is stable or rising. Consequently, hillslopes are relaxing and accumulating soil, thus developing deep weathering profiles.

The fine scale study illuminates differences in hillslope behaviour in the two drainage systems with contrasting base-level control. The soil residence time data for Hoffman-Peterson Creeks (Figure 2 - red) is log-normally distributed with a mean of ~10 ky, consistent with the expected residence time for steady state erosion at 0.10 - 0.15 mmy^{-1}. We suggest that the variation in residence time values (std. dev is 6-14 ky) reflects intrinsic stochasticity of processes of soil production and transport that ultimately drive variability of denudation at the divides where we sampled. The North Fork Smith River samples are more variable (std dev = 14-47 ky), have a larger mean (21 ky), and exhibit a long-tail, approximated by a power law (Figure 2 - blue). The abundance of long residence time soils likely reflects reduced base-level lowering and slow denudation in the catchment above North Fork Falls. We propose that our Hoffman Creek data reflect random variability for a catchment that approximates a 'steady-state' condition. For the North Fork Smith River site, by contrast, the heavy tail of the residence time distribution reflects slow-eroding surfaces upstream of the knickpoint, while the shorter residence time soils result from impingement of surrounding catchments and drainage divide migration.

Conclusion

Soil residence time in the Oregon Coast Range supports the contention of an approximate equality of erosion rate and regional rock uplift rate over large areas. However, long soil residence times in some parts of the landscape highlight decoupling from base-level lowering, resulting from large scale drainage realignment or smaller scale fluvial or mass movement modification of topography. A detailed study of the distribution of soil residence time in two small catchments with contrasting base level controls identified contrasting patterns of erosion. These data provide spatially-extensive, quantitative constraints on landscape dynamics at geomorphic timescales and should be useful for calibrating emerging stochastic models for hillslope evolution.

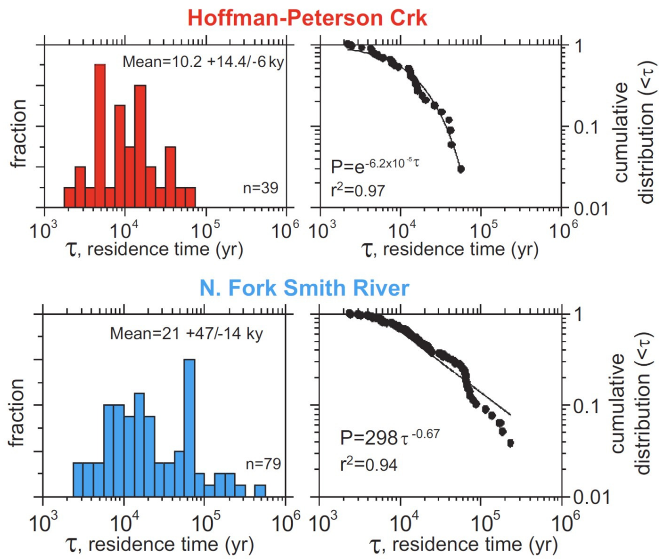

Figure 2. Frequency distributions for soil residence time for the Hoffman-Peterson and North Fork Smith drainages.

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