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

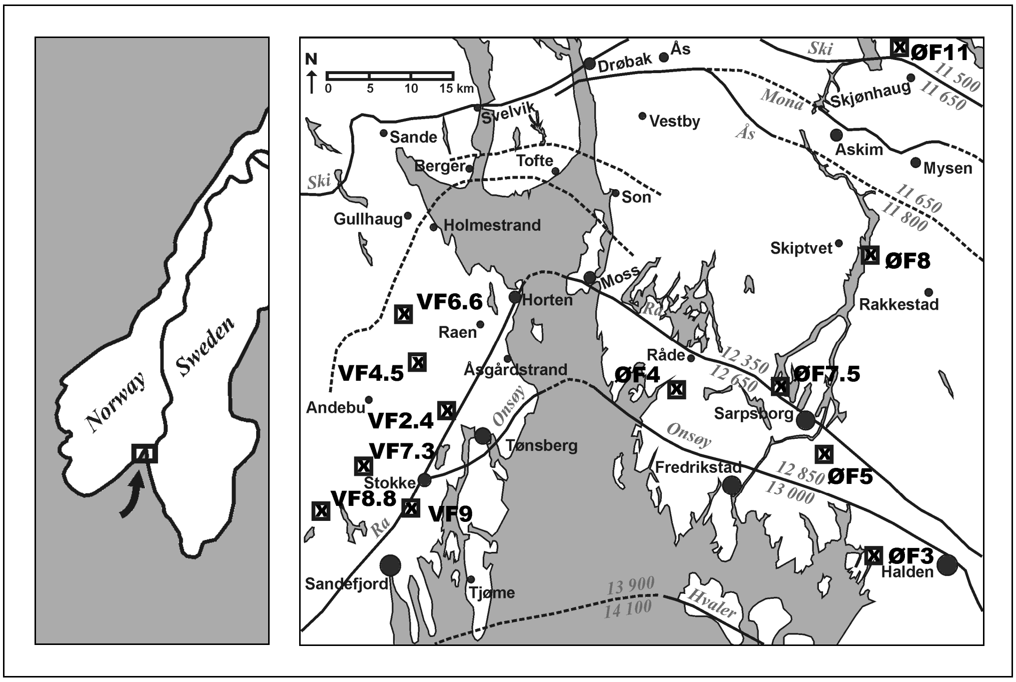

Figure 1. Location of the study area (left) and pedons (right) (Sørensen 1979; 1992). Black lines indicate locations of moraines; the time spans of moraine formation are indicated in cal yrs BP (after Ramberg *et al.* 2006). At the time of glacier retreat, the whole area was below sea level.

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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