Schjønning, P., Keller, T., Alakukku, L., Børresen, T., Dørsch, P., Jarvis, N. 2013. Extract from the final report re the POSEIDON project (www.poseidon-nordic.dk)

In the following, we will present results obtained during the POSEIDON project period. Space allows only display and discussion of selected data. Please consult the papers listed in the main report for more results. Some data are yet unpublished and presently being prepared for presentation in peer-reviewed papers.

Although the POSEIDON project primarily focused the persistent / long-term effects of soil compaction, the present overview includes a short paragraph on the immediate effects of wheel traffic on soil properties. We included such studies in the project in order to enhance our understanding of how the soil pores are affected. Soil ecosystem functions and services are linked to the soil pore system. A better understanding of the compaction effects on distortion and reduction of soil voids may facilitate the interpretation of the long-term effects.

One paragraph reports on compaction effects on basic soil properties, which was measured by standard laboratory methodologies. Our sampling strategy in the long-term field experiments allowed us to cover the variability across the fields, which enhances the possibility of revealing the compaction effects. Two paragraphs report the field-scale measurements of gas and water dynamics, respectively. Main conclusions from the studies are given in a final paragraph.

Immediate compaction effects on soil properties

We identified a spatially homogeneous clay loam soil in Switzerland developed on alluvial sediments. As part of the PhD study of Feto Esimo Berisso linked to the POSEIDON project, a wheeling experiment was performed with the objectives (i) to investigate the impact of the passage of an agricultural tyre on the soil pore system and its functioning at various depths and at various lateral distances from the tyre centreline, and (ii) to relate the changes in soil physical properties to the stress field induced by the tyre. Figure 1 presents air-filled porosity, ε_a, and air permeability, k_a, as a function of depth below the wheel rut and lateral distance from the centre of the wheel rut. It is interesting that ε_a decreased towards the centre of the wheel rut (similar results were obtained for total porosity; not shown), while k_a had a minimum close to the edge of the wheel rut (Fig. 1). The changes in ε_a and k_a could be related to the stress field induced by the tyre, and we could show that ε_a was a function of the mean normal stress ("compressive stress"), while k_a was affected by both the mean normal stress (pores become smaller) and shear stresses (pores become distorted or disconnected).

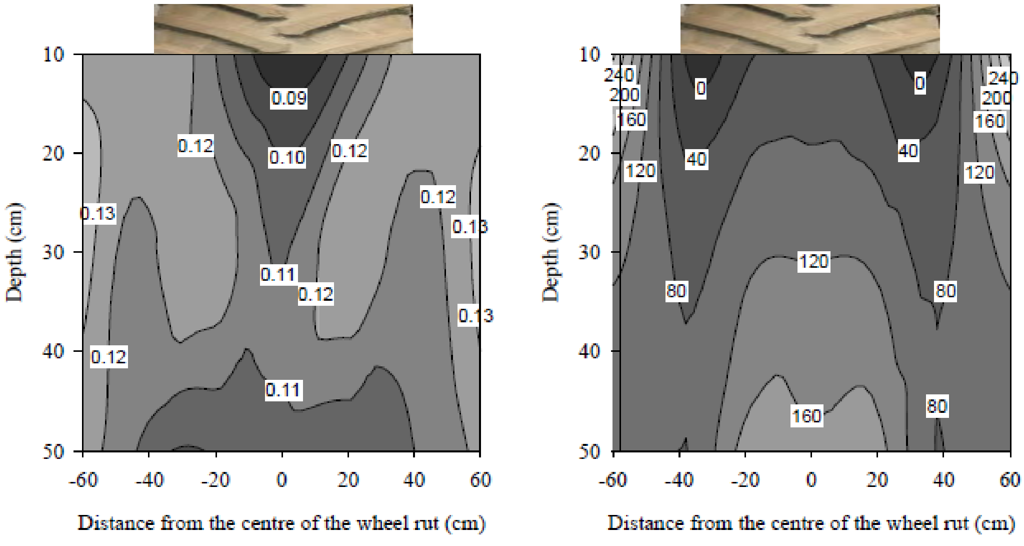


Figure 1. Isolines for air-filled pore space (m^3 m^{-3}, left) and air permeability (μm^2, right) for soil at 10-50 cm depth across the wheel track.

Long-term compaction effects on soil physical properties

Several of the soil cores collected in the field experiments were scanned with a medical CT scanner, which proved beneficial in our evaluation of the compaction effects on the pore system. As an example, Figure 2 shows two selected cores from 50 cm depth of the long-term Jokioinen experiment. Averaged across the replicate cores, the CT estimates of macropores were significantly reduced for compacted soil (0.010 m^3 m^{-3}) compared to control (0.026 m^3 m^{-3}). The same trend was observed at 25-45 cm depth for soil cores collected at the Brahmehem experiment, although not statistically significant. However, at that location the vertical distribution of CT-estimated air-filled macroporosity indicated biological activity to be largest in the top of the soil columns from the compacted plots, while reduction of macroporosity was significant at the bottom of the same columns (cf. Status Report from 2010).

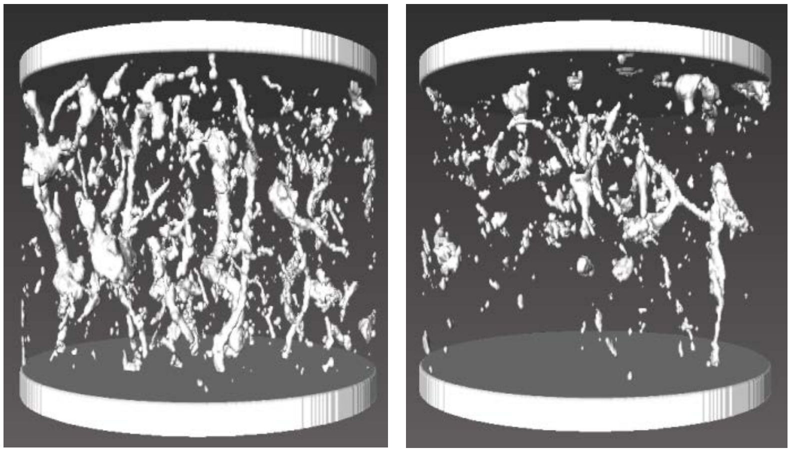


Figure 2. CT-visualization of soil pores (resolution: 300×300×600 µm) in 8 cm high and 10 cm wide soil cores collected in 50 cm depth of the Jokioinen experiment. The selected cores represent the one out of eight replicate cores closest to the median value for each treatment (left: control; right: compacted 29 years to sampling). The two cores are from the same field block.

Based on water retention measurements for soil cores collected at four depths at the Brahmehem location, we were able to identify significant compaction effects to 90 cm depth (Fig. 3). We applied a double exponential model that described well the dual porosity for this sandy clay loam developed on glacial deposits. In short, the C+A1 fraction displayed in Figure 3 is labeled the textural porosity (small pores), while the A2 and A3 fractions are labeled the structural porosity and the non-capillary macropores, respectively. The structural porosity (A2) correlated to the volume of capillary macropores >30 µm and was significantly reduced for all depths examined (Fig. 3; P=0.1 at 0.7 and 0.9 m). For the 30 cm depth, also the non-capillary macropores, which may be interpreted as biopores, were significantly reduced (P=0.1).

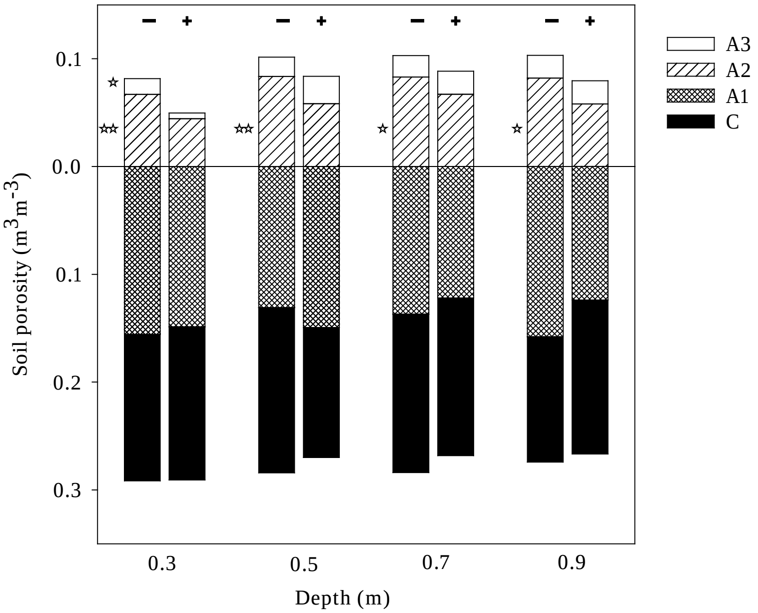


Figure 3. Pore size fractions at four soil depths of the Brahmehem soil profile for control (-) and compacted (+) soil. Significant differences are denoted by a single asterisk (P=0.1) or double asterisks (P=0.05). The A3, A2 and A1+C soil pore fractions should be considered non-capillary macropores, capillary macropores, and textural pores, respectively (please consult text for further explanation).

In accordance with the observed persistent compaction effect on the volume of pores > 30 µm, we found a reduction in the conditions for gas transport by diffusion as well as convection when the soil was drained to pF2, which corresponds to field capacity (Fig. 4). Relative gas diffusivities less than 0.005 are expected to be critical for aerobic soil processes. Based on this, the Brahmehem soil can generally be characterized as close to the critical limit, and the compaction has reduced the diffusivity to levels below the limit for all depths examined. The compaction effects discussed here were significant at the P=0.05 level only for relative diffusivity at 0.3 m and for air permeability for 0.3 and 0.9 m (Fig. 4). However, the same trend was found for other depths with P-values generally less than 0.19. A repeated measurement test including all depths showed both gas transport properties to be significantly reduced by heavy compaction in the whole soil profile (data not shown).

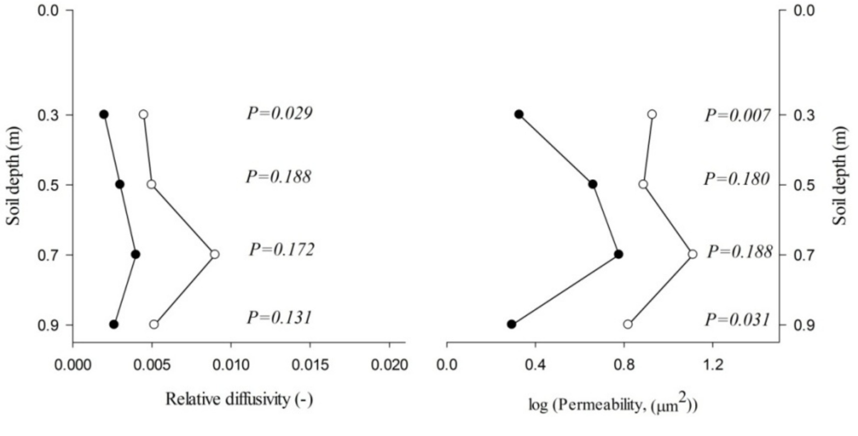


Figure 4. Relative gas diffusivity (left) and air permeability (right) for soil drained to pF2 for control (open symbols) and compacted soil (closed symbols) at four depths of the Brahmehem soil. P-values indicate probability of the observed difference being due to random variation (F-tests).

Also the conditions for water flow were affected by the experimental traffic at the Brahmehem soil 14 years prior to our sampling (Table 1). For both series of measurements (small or larger cylinders), we found a considerable reduction of saturated water conductivity amounting to 1/8 or 1/6 the level of control soil, although statistically significant only for the large cores. Also at the 50 cm depth, we estimated a considerable decrease in compacted soil, although not statistically significant (P=0.14).

Table 1. Saturated hydraulic conductivity, mm h^{-1}, measured by steady-state methods in the laboratory with two different sizes of cores. Numbers labeled with the same letter within a core size are not statistically significant (P=0.05).

Depth (cm)	200 cm^3 cores		~6 liter cores	
	Control	Compacted	Control	Compacted
30	75.9a	10.0a	55.8a	10.0b
50	147a	36.0a		
70	96.0a	30.0a	39.2a	49.6a
70	8.5a	7.8a		

The laboratory studies summarized above generally indicate persistent effects of compaction on physical soil properties. Based on this, we hypothesized that field scale processes in the gas as well as water phase would be affected.

Long-term compaction effects on soil water transport in the soil profile

Using tension infiltrometers at the 30 cm depth of the Brahmehem experiment, we found a (non-significant) trend of higher unsaturated conductivity at tensions very close to saturation for control compared to compacted soil (data not shown). This is in accordance with the observations in the laboratory (Table 1). Interestingly, this pattern changed when draining the soil to tensions lower (more suction) than ~-10 hPa. The same was observed by drip infiltrometer measurements on ~6 liter cores in the laboratory (data not shown). This may indicate an increase in the volume of mesopores deriving from the reduction of macropores in soil that experienced compaction.

Leaching experiments at controlled conditions in the laboratory did not indicate any compaction effects on the degree of preferential flow as judged from solute breakthrough curves (data not shown). We did these tests for soil cores collected at the long-term Brahmehem experiment as well as for the new compaction experiment at Säby near Uppsala.

A field-scale infiltration experiment with dyed water indicated that dye coverage was significantly lower in the control treatment at 0.2-0.25 cm depth, i.e. just above the subsoil (Fig. 5). We associate this with the decrease in hydraulic conductivity in the underlying compacted layer, which led to temporary accumulation of 'perched' water above the compacted layer. The reduction of saturated and near-saturated hydraulic conductivity resulted in a confinement of solute transport to a smaller part of the pore space in the compacted treatment, which is seen in significantly lower dye coverage in the compacted treatment at 0.35-0.4 m depth (Fig. 5). Differences in dye coverage at 0.6-0.8 m depth (Fig. 5) were strongly related to differences in soil texture between plots, where dyed patches correlated with the location of sand lenses. Similar results as for the dye coverage were obtained when analysing the number of flow paths or the metric entropy.

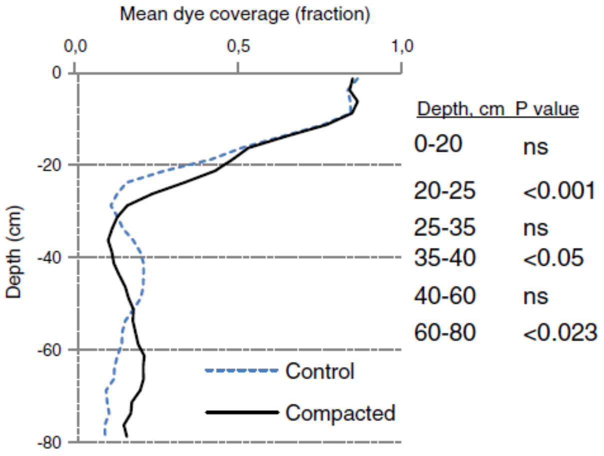
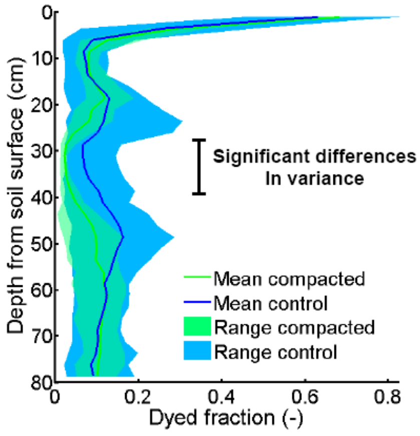


Figure 5 (left). Average dye coverage in 2.5 cm thick layers at Brahmehem.

Figure 6 (right). Average and range in dye coverage in 2.5 cm thick layers new compaction experiment at Säby near Uppsala.



Dye tracer experiments from the new compaction experiment at Säby, Uppsala, seem to support the results from Brahmehem (Fig. 6). The significantly lower variance of dyed fraction around the statistically similar estimates of mean dyed fraction may be interpreted as a reduction in the volume of mesopores for the compacted soil.

Long-term compaction effects on production and emission of greenhouse gases

Laboratory incubations were carried out with disturbed and undisturbed soils to characterize denitrification and N_2O production in compacted and non-compacted subsoil in more detail. Aerobic respiration, potential denitrification and denitrification product ratios (N_2O/N_2) were determined in soil slurries amended with NO_3^- under oxic and anoxic conditions, respectively. The results showed that microbial activity and denitrification potentials decreased by 3 orders of magnitude from the topsoil to 90 cm depth, independently of soil compaction (data not shown). N_2O/N_2 product ratios tended to be higher in compacted than in non-compacted subsoil, but this effect was quite variable and statistically insignificant (data not shown). It can be concluded that long-term compaction below the plough layer has not resulted in a persistent shift of potential denitrification and its product stoichiometry in the subsoil, which is important with respect to ground water protection. Undisturbed subsoil samples equilibrated to different matric potentials were used to see whether soil structural differences imposed by compaction would affect N_2O production. After amending the soil cores with mmolar concentrations of NO_3^- and glutamate, measurable N_2O production was observed in oxic incubations, however with no significant difference between compacted and non-compacted treatments (data not shown). Again, inducible N_2O emission in intact soil cores was 1-2 orders of magnitude lower in the subsoil as compared with topsoil.

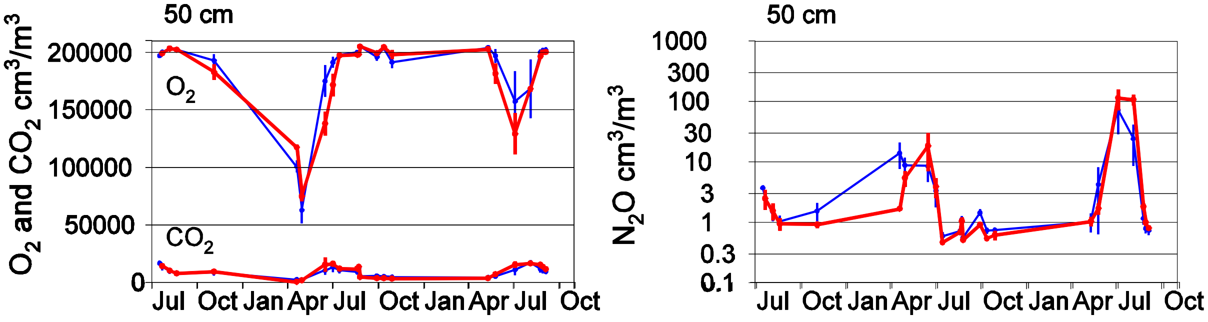


Figure 7. Soil air composition at 50 cm soil depth in the Jokioinen field (Jul 2009 – Sep 2011) for control (blue) and compacted soil (red).

In Jokioinen, the seasonal variation of *in situ* soil air composition was pronounced, occasionally with O_2 concentrations less than 10-15 vol-% in deeper subsoil, but the effects of persistent subsoil compaction were rather small. However, in summer 2010, the low O_2 concentrations in deeper subsoil horizons were increased back to atmospheric levels more slowly compared with the control soil (shown for 50 cm depth in Figure 7). N_2O concentrations were highest in the topsoil. High N_2O concentrations above 100 ppmv were observed in July and August 2011 after the N-fertigation campaign (June 2011). The variation in soil gas concentrations at the Brahmehem experiment was less pronounced (data not shown). The effect of compaction on N_2O concentrations was always rather small and variable.

The annual fluxes of N_2O (mean ± SD) during Oct. 2009 – Sep. 2010 in the control and compacted treatments, respectively, were 8.6 ± 3.7 and 9.4 ± 1.0 kg N ha^{-1} in Finland, and 10.0 ± 4.1 and 8.3 ± 3.8 kg N ha^{-1} in Sweden, with no significant differences between the treatments (Fig. 8).

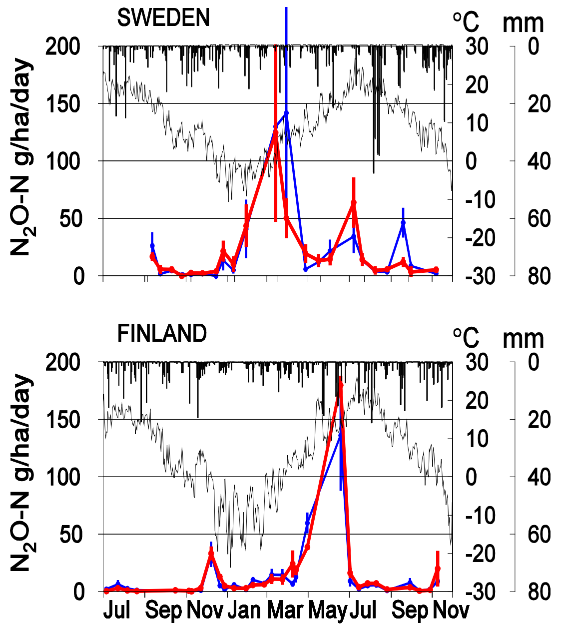


Figure 8. Nitrous oxide emissions from soil in the Brahmehem and Jokioinen fields (2009–2010) for control (blue) and compacted (red) soil. Bars give daily precipitation and black line indicate air temperature.

N_2O emission rates correlated positively with N_2O concentrations at the depths of 15, 30, 50 and 70 cm in both fields (r = 0.4-0.7***; analyses not shown). Compaction tended to increase the N_2O concentration in soil air. The oxygen concentrations in the subsoil correlated negatively with the N_2O emission, but only at the Finnish site. The results suggest that despite periods of impaired subsoil aeration and higher concentrations of N_2O in soil air, subsoil compaction does not significantly increase N_2O emissions from these soils to the atmosphere 15-30 years after compaction. This indicates a minor role of subsoil for the overall emission of N_2O to the atmosphere.

Fertigation experiments were conducted at both sites to provoke conditions conductive to denitrification throughout the entire soil column (high NO_3^- concentration and high soil moisture). In both experiments, N_2O flux and soil air concentrations measured shortly after fertigation were low and showed high variability within treatments, rendering observed differences between compacted and non-compacted sites statistically insignificant. It has to be stated that the weather during the Brahemehem campaign was colder and during the Jokioinen warmer and drier than normal for the seasons. This may explain observed low N_2O emission rates despite fertilizer N addition and high soil moisture. Additional flux measurements were carried out at the Jokioinen site 4 days after fertigation when rain events led to increasing water table. At this point, N_2O emissions were 10 times higher than the average flux measured after fertigation and slightly higher in the non-compacted than in the compacted site. The Jokioinen fertigation experiment was done with ^{15}N-labelled NO_3^- in order to i) apportion the source of N_2O emission (i.e. nitrification vs. denitrification), ii) quantify the total fertilizer-derived *in situ* denitrification (N_2O + N_2) and iii) calculate the contribution of different soil layers to total emitted N_2O and N_2. Most of the added ^{15}N was retained in the top soil (0-20cm), but ^{15}N in pore water nitrate sampled by suction lysimeters from 50 and 70 cm depth as well as in NO_3^- extracted from bulk soil sampled from the same depths 4 hours after label application was higher in compacted than in non-compacted soils. This indicates that added NO_3^- moved somewhat faster to the subsoil in compacted than in non-compacted soil, possibly owing to more preferential flow in the compacted soil (cf discussion above). Comparing ^{15}N recovery in pore water and in soil extracts along depth revealed uneven vertical distribution of ^{15}N label between the bulk soil NO_3^- pool and the pore water NO_3^- pool. This complicates N_2O source apportionment and estimation of *in situ* denitrification. According to preliminary results of ^{15}N abundance in N_2O and N_2, N_2 was the main product of denitrification accounting for >80% of gaseous N emission. The ^{15}N abundance in N_2O was consistently lower than that of the nitrate pool in the topsoil, indicating that either some N_2O was produced in deeper soil layers (with lower $^{15}NO_3$), or that N_2O from nitrification (oxidizing non-labelled NH_4^+) contributed to soil-atmosphere N_2O exchange. There were no significant differences in N_2O and N_2O 15N abundances between compacted and non-compacted soils (data not shown).

Conclusions

The studies in POSEIDON document persistent effects of compaction on basic soil physical properties to a depth of 90 cm. This includes reduction of the volume of soil voids, especially those larger than approximately 30 μm. Our studies of the immediate effects of wheel traffic indicate that distortion of the soil pore system in the upper part of the B-horizon probably adds to the effects on soil functions related to the isotropic reduction of the voids. Accordingly, we found persistent constraints in gas diffusion, air permeability and saturated / near saturated hydraulic conductivity of subsoil layers at two long-term field experiments 14 and 29 years after the experimental traffic had been inflicted.

The results obtained in the field on gas as well as water dynamics were much less clear regarding the effects of persistent subsoil compaction. This relates to considerable variation in space and time.

Field measurements of water conductivity confirmed laboratory results, but with no significant difference between control and compacted soil. Field irrigation with dyed water as well as the fertigation experiment indicated ponding of water above layers with specifically low water conductivity. The distribution of dye in the soil profile confirmed the general knowledge that preferential flow in macropores occurs in structured soils. However, the high variability of the soil studied hampered a clear indication of the extent to which soil compaction enhanced preferential flow. Neither did solute breakthrough studies in controlled irrigation experiments in the lab indicate a pronounced effect of compaction.

Our studies on soil gas concentration and surface gas emission gave indications of compaction effects on the concentrations of oxygen and N_2O in the soil profile. Although our data pointed to a minor direct role of the subsoil for N_2O soil-atmosphere flux, the estimated annual gaseous losses of N were relatively high and encourage further studies on the subject.

Perspectives

The combined study on vertically and horizontally sampled soil cores in POSEIDON revealed important knowledge of soil functions (these results were not included in the final report,- see the list of publications for further information). Further studies of gas and water transport may benefit from including the anisotropy aspect.

One of the tested hypotheses in the POSEIDON project was that persistent subsoil compaction would lead to higher N_2O emissions due to changes in soil properties, including solute and gaseous conductivities of the soil pore system. Based on N_2O emission measurements at two sites differing in soil type and climate, we concluded that a singular event of heavy traffic had no measurable effect on N_2O emissions about 14 years, and respectively 29 years, after the event. In general, as judged from activity measurements in the laboratory, microbial N-transformations in subsoils contributed little to soil-atmosphere N_2O exchange in the experimental fields. Hence, structural changes below the plough layer were unlikely to directly affect N_2O emissions. However, the project paid less attention to the indirect effects of subsoil compaction on topsoil processes that affect nutrient turnover and GHG emissions. Any change in subsoil structure affecting solute and gaseous transport parameters in the topsoil is likely to affect root processes and the competition between plants and microbes for nutrients, both of which may impact greenhouse gas (GHG) formation and emission. Therefore, future studies should put more emphasis on feedbacks of subsoil compaction to topsoil processes, including effects on plant root functions. Likewise, a future focus should be on wet topsoil conditions due to subsoil compaction, which may increase the risk of topsoil compaction and hence soil processes relevant to gas exhange and water movement.

Another track of thought which could not be fully resolved in the present project is the effect of structural change of subsoils on biological nitrogen retention/removal. Subsoils are commonly considered important "filters" attenuating the nitrate burden to groundwaters from heavily fertilized cultivated soils. This function may be sensible to subtle changes in flow patterns induced by compaction (see below), but little is known about how this interacts with the ecology of the organisms mediating this function. Ultimately, our understanding of subsoil denitrification could be greatly advanced by assessing the temporal and spatial dynamics of substrate availability in the nutrient poor subsoil environment. The present project has brought together techniques (tracer experiments, dye experiments, CT scans) which will be useful in future experiments operating at a higher temporal and spatial resolution.

Another hypothesis we wished to test in POSEIDON was that persistent subsoil compaction would increase leaching of surface applied contaminants (e.g. pesticides), because the frequency and severity of preferential transport in soil macropores would increase. The hypothesis follows from the idea derived from percolation theory, that water flow and solute transport in disordered (i.e. strongly heterogeneous) pore systems is primarily controlled by the largest continuous pores. If compaction decreases hydraulic conductivity near saturation because some macropores are disrupted or destroyed, then water will flow in larger pores than it otherwise would have done, providing some of these remain intact. During the POSEIDON project, our understanding of this concept has further developed, at least in principle. There may be a need to modify the original hypothesis to state that compaction should increase preferential transport up to a point, but that increased severity of compaction beyond this point, will lead to reduced solute transport velocities because pore continuity will become limiting (no larger continuous pores remain). Further studies would benefit from including the resilience aspect in recovery of macropores, for example by biological activity. Also, our studies emphasize the importance of soil pore distortion from shear stresses.

In POSEIDON, we tested the hypothesis of compaction-induced increase in leaching of surface applied contaminants with dye tracing experiments at the Brahmehem field site in Sweden. The results did seem to confirm the hypothesis, although the differences in dye patterns between compacted and un-compacted treatments were small and quite advanced statistical methods were needed to detect them. We also carried out solute transport experiments on soil columns taken from the Brahmehem field as well as a field site with a control treatment and recently compacted subsoil at Säby in Sweden. The results from the Säby experiment have not yet been fully analyzed but based on the Brahmehem data and preliminary analyses of the Säby data, there seems to be no significant effect of compaction on the degree of preferential flow. The seemingly minor compaction effect may relate to the fact that the soils studied displayed preferential flow also for the control plots, partly due a high degree of anisotropy especially of the soil layer beneath the ploughing depth (the 'plough pan').

One difficulty encountered in POSEIDON, which is apparent in the results from both field experiments where solute transport was studied, was the large spatial variation in texture and structure, which tended to obscure and overshadow the treatment effects (i.e. the single compaction events that were imposed). In the future, it would be interesting to study the effects of compaction on soil pore systems and water flow and solute transport in a more dynamic way. In other words, to study the effects of recurrent traffic and compaction events in relation to the recovery and regeneration of soil structure by physical and biological processes. This implies continuous monitoring of long-term experiments with treatments under different management systems (e.g. conventional vs. controlled traffic) and would involve measurements made on samples taken at regular intervals from the field plots, for example combining flow and transport experiments (measurement of near-saturated hydraulic conductivity and solute breakthrough curves) with X-ray scanning of the soil pore system in the same samples.

In addition to spatial variability, it seems that we have a "problem" when moving from the soil core/column size to the profile scale. Although we can measure significant differences in pore space and functions on the soil cores, we have difficulties seeing effects when we look at the whole profile (e.g. dye tracer experiments). So, more studies on larger scales or studies combining various scales and the associated inherent anisotropy are needed.

Especially for the gas dynamics, there is an additional challenge in the temporal variability of aeration status of the soil and the associated potential peaks of surface emission. This may be addressed by enhanced strategies in field monitoring. Another potential concurrent approach would be studies on undisturbed soil cores in controlled environments in the laboratory combined with modeling of the processes at field scale.