Summary and conclusion

Soil contamination by mineral oils and mineral oil products is a matter of rising importance. Reclamation of contaminated soils is expensive, energy consuming and laborious, while public means are limited. Phytoremediation may be a promising low cost alternative. Support of natural decomposition processes ("natural attenuation") carries the potential to serve as a cost efficient method to reduce the risks caused by soils which are contaminated with hydrocarbons.

The aim of this work was to make a statement about plant species suitable for the protection and long-term decontamination of large contaminated areas. This purpose was to be achieved by means of specific soil analyses and pilot tests.

Phytoremediation means to support microbiological transformation processes in the soil through the introduction of selected plant species. The effect of such selected plants is supposedly based on their beneficial influence on microbiological activity in the rhizosphere.

At the locations selected for this study, the distribution of toxins was extremely heterogeneous. Next to nearly clean areas there were contaminated areas which contained mineral oil - hydrocarbons up to 167.000 mg/kg and polycyclic aromatic hydrocarbons up to 301 mg/kg. Additionally, hydrocarbon deposits were characterized by consistencies between moist-pasty and solid. Due to additional uncontrolled deposition of rubbish and rubble, significant concentrations of heavy metals were found (Cu: 106 mg/kg, Zn: 301 mg/kg, Pb: 183 mg/kg).

Surprisingly, even heavily contaminated patches were found to be colonized by higher plants. Apart from species typical of wastelands as Elder (*Sambucus nigra*), Ash (*Fraxinius excelsior*) and a variety of grasses, also Alder (*Alnus glutinosa*), Willow (*Salix alba*), Reedmace and Reed were found.

Strongly contaminated areas were covered with plants, including a good root growth.

The existence of reed and other species of moist habitats was more caused by natural conditions (moist conditions) than by contamination.

Lumbricide diversity was also influenced by other factors than contamination. Feeding activity of soil fauna (bait lamina test) was significantly reduced in strongly contaminated areas. Further contamination led to a reduction of ß - Glucosidase activity and Arginin - Ammonification as well as to an increased metabolic quotient. The microbiological biomass of contaminated samples was lower than that from non contaminated samples taken from the same location.

After previous vegetation studies we chose plant species with a large ecological amplitude. The selected species were Reedmace *(Thypha latifolia)*, Reed *(Phragmites australis)*, Willow *(Salix alba)* and Alder *(Alnus glutinosa)*. The suitability of Alfalfa *(Medicago sativa)* and Mulberry *(Morus alba)* has already been previously published, while Reed Canary Grass *(Phalaris arundinacea)* was examined in the course of preliminary work (HÜBNER et al., 2000).

These plants were able to penetrate pasty asphalt material (decomposition tests) as well as the solid asphalt layer of 3 cm thickness (penetration tests).

In pot experiments (decomposition tests) I found a reduction of hydrocarbon content (highest dosage was 111.000 mg/kg soil) in comparison with nonvegetated pots. Within 3 vegetation periods the content of mineral oil - hydrocarbons decreased more than 94 % in a sandy substrate planted with Reed. Tests with loamy substrates and

mineral oil - hydrocarbon content of up to 89.000 mg/kg soil, yielded a reduction of these toxins up to 81% within 2 years.
Plant specific differences were found. There was a significantly* higher reduction of hydrocarbons on planted areas, compared with unplanted areas. The calculated stimulation ratio is shown: **Alfalfa* +37,4 % > Willow* +33,0 > Alder* + 30,7% > Reed* +18,9 % > Mulberry* 16,5 % > Black Locust* +13,2 % > Reed Canary Grass +6,7 %.** Tests with Reedmace had to be abandoned due to poor growth.
The main part of microbiological decomposed mineral oil - hydrocarbons was incorporated into soil organic matter (C_{bioorg}). Especially in variations with Alder, Black Locust and Reed Canary Grass mainly humification processes took place, whereas with other species mineralisation and other processes were predominant.
Consumption of nitrate in treatments with asphalt content exceeded consumption in variations without asphalt by a factor of 10. Nitrate uptake by plants and its function as an electron acceptor in connection with the microbiological toxin transfer has to be considered at the same time.
In treatments with Alfalfa and Alder, a higher nitrogen content in the soil as well as within the plants was correlated with the reduction of mineral oil. Other nutrients (P, K) indicated smaller differences.
Further nitrate supply influenced root growth ($r = 0{,}53$; $\alpha = 0{,}05$; $n = 62$) and the microbiological biomass ($r = 0{,}58$, $\alpha = 0{,}05$; $n = 62$). The potential employment of microbiological cleaning processes depends on the availability of hydrocarbons as an energy source as well as on the availability of essential nutrients for micro-organisms. For this reason, a potential change in sorption characteristics of the contaminated soil needs to be considered. Potential cation exchange capacity (CEC) in test substrates was significantly reduced, with extreme values in the range of only 10 % of the CEC in non contaminated soil.
Microbiological biomass increased in size as a result of planting. This correlated with basal respiration ($r = 0{,}87$; $\alpha = 0{,}05$; $n = 62$). Catalase- and ß-Glucosidase activity increased as well with reference to unvegetated pots.
I did not find a correlation between the amount of microbiological biomass, Catalase- / ß - Glucosidase activity and toxin decomposition. The metabolic quotient (qCO_2) and respiratory quotient (Q_R) increased by contamination. Both parameters are suitable for the assessment of damage in contaminated soil ecosystems. The metabolic quotient correlated with basal respiration ($r = 67$; $\alpha = 0{,}05$; $n = 62$). Inhibition of biological activity as detected by tests with luminous bacteria (*Photobacterium phosphoreum*) (toxicity screening) corresponded with toxin content ($r = 0{,}71$; $\alpha = 0{,}05$; $n = 0{,}62$).
As seperate plant species have very different demands on environmental conditions, there are several possibilities for the employment of phytoremediation technology. Due to largely unrestricted growth in contaminated soil substrates, Reed, Alfalfa, Alder, Mulberry and Black Locust seem to be particular suitable for such purposes. I hypothesize that an appropriate vegetation cover not only stimulates the decomposition of contaminants, but may as well reduce the percolation loss of contaminated seepage water by an enhancement of evapotranspiration.
Decontamination and protection activities may change soil organic matter levels in remediated soils. Soil organic matter losses were higher in revegetation experiments with Alfalfa and Reed, than in treatments with Alder. This may be interpreted as increased incorporation of contaminant carbon into soil organic matter following

revegetation with Alder. In our investigation, it was neither intended nor practicable to calculate a precise soil carbon budget. Monitoring of C_{bioorg} - values, however, should yield information pertaining to humification processes and consequently to the progress of reclamation activities. Activities of this kind are strongly recommended, as information about the reversibility of metabolite sorption and their longtime persistence in soils is incomplete and inconsistent.
We lack both (i) procedures for the detailed assessment of contaminant transformation mechanisms and (ii) methods for a improved determination of suitable microbiological parameters. These deficits are associated with the origin of the procedures employed from traditional soil fertility analysis.
Further investigations into the reclamation of hydrocarbon contaminated soils need to include the determination of potential effects on cation exchange capacity (CEC).
This work has clearly demonstrated, that asphalt additions have a large and diminshing effect on CEC. The methodology used, however, proved to be unsatisfactory for the purpose and the special properties of the substrate.
At this time, "low cost" phytoremediation seems to have its biggest potential in situations, where time is not a critical factor.
Continued research activities are required to (i) improve the efficiency of such practice and to (ii) convince decision makers in business and administration of the large beneficial potential inherent to phytoremediation activities.