PROGRAMM LEBENSGRUNDLAGE UMWELT UND
IHRE SICHERUNG (BWPLUS)

Biologische und ökotoxikologische Bewertung von Böden in Ballungsräumen

Biological and Ecotoxicological Evaluation of Urban Soils

Final Report

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1 Introduction

1.1 Basic problem

Despite a marginal population growth in Germany, 117 ha agricultural land are being converted for housing or traffic every day (UMWELTBUNDESAMT, 2002). In Baden-Württemberg, 11 ha soil are lost every day, with the consequence that between 1993 and 2003 - contradictory to the aim of the environmental plan - the area for housing and traffic was not reduced markedly but rather increased by 9 % (LANDESANSTALT FÜR UMWELTSCHUTZ, 2003). Normally, the affected soils experience a pronounced and mostly irreversible loss of functions due to sealing, compaction, degradation, landfilling or mixing. Soils that have developed over thousands of years are lost. Soils, however, have varying functions beside supporting housing and traffic. They primarily fulfill a wealth of ecological functions (Federal Soil Protection Act: BBodSchG; DEUTSCHER BUNDESTAG, 1998). Soils support plant growth, serve as habitats for soil organisms, and filter, buffer and transform pollutants. Furthermore, soils balance the water cycle and help regulate the climate.

To counteract this superproportional loss of natural soils, the sustainable protection and restoration of soil functions were specified fixed in 1999 as overriding environmental tasks in 1999 in §1 BBodSchG. In addition, soils should be treated economically and with respect when compiling land use plans and in urban land use planning (PLANUNGSGRUPPE ÖKOLOGIE + UMWELT GmbH, 2003). Morevover, according to the Federal Nature Conservation Act (BNatSchG), soil is defined as a subject of protection and can be taken into consideration when compiling landscape plans. Inevitable soil use should be directed to areas with comparatively low importance for soil functions or to areas where compensation is largely possible.

According to §2(2)1.a) BBodSchG, soils fulfill the natural function as a basis for life and habitat serve as a habitat for humans, animals, plants and soil organisms - the pivotal soil function (HOLZWARTH et al., 1998). In urban soils this function is especially affected by human activities such as sealing, compaction, degradation, landfilling or mixing. If urban soils should be treated economically and with respect in urban planning, then their functions have to be surveyed and evaluated quantitatively and qualitatively. However, the habitat function of the soil has not yet been set down in the Federal Soil Protection And Site Contamination Ordinance (BBodSchV: BUNDESMINISTERIUM FÜR UMWELT, NATURSCHUTZ UND REAKTORSICHERHEIT, 1999). The reason for this is that a sufficient number of validated test methods have only become available recently, but a generally accepted testing strategy is still missing (KÖRDEL & RÖMBKE, 2001). Finally, no appropriate evaluation procedure is

available to evaluate the sub-function habitat as a habitat for soil (micro)organisms and fauna: this calls especially for methods to evaluate the criterion “suitability of sites for communities of soil (micro)organisms” (AD-HOC-AG BODEN, 2003; RÖMBKE et al., 2002).

1.2 Effects of human activities on the soil habitat

Human activities modify soils, thereby setting off anthropogenic lithogenesis and pedogenesis, particularly by imposing very rapid transformation cycles (BLUME, 1996; DE KIMPE & MOREL, 2000). These different activities vary in the degree to which they interfer with the habitat function of soils for organisms. Although detailed soil biological studies are missing, some general statements can be made (HOCHFELD, 2000). The detrimental effects of ecotoxicologially active compounds, e.g. heavy metals or organic pollutants will not be considered here because they are covered by the BBodSchV.

The main abiotic soil factor related to the habitat function is pore space (HOCHFELD, 2000). Any alteration or destruction of the pore space directly affects habitat quality. Furthermore, the water balance, which is closely related to soil air balance, plays a pivotal role. The composition of the solid phase is highly relevant for characterizing habitat quality. Close interactions between quality and quantity of soil organic matter and the soil community exist. Finally, soil temperature affects the soil organisms. As abiotic soil factors vary with depth and time, the soil community is part of a highly dynamic system.

Soil sealing destroys soil habitats by hampering gas and water exchange and by hindering the displacement of the flora and fauna. The microorganisms do continue with humus mineralization, but only to a minor extent. The degree of regeneration after unsealing is unclear. Totally sealed soil is probably the worst soil property with respect to habitat function.

Compared to sealing, soil degradation differs in its effects on the habitat because water and stock flows are still possible. Furthermore, soil development can resume after degradation, resulting in the establishment of a new soil community. Any evaluation of degraded soils should therefore consider the thickness of the degradaded layer in relation to the thickness of the soil profile and the degree of regeneration. The impact of erosion, e.g. after removing the vegetation, is comparable to degradation, although the biocoenosis has more time to accommodate. Crucial for evaluation are erosion rates and the thickness of soil loss. With respect to the habitat function, landfilling should be considered comparable to soil degradation. The thickness and properties of the landfill are crucial for the soil community.

Non-recurring compaction has minor effects on the biocoenosis because comparable habitats emerge due to the activity of the soil community. Repeated compaction, on the other hand,

hampers regeneration and alters the biocoenosis. Soil mixing mainly alters physical properties and results in homogenized soil properties, but the habitat quality of natural soils does not improve. In general, macrofaunal diversity is affected, but a semi-natural biocoenosis develops soon after soil mixing.

The input of airborne nutrients and fertilizers to soils results in shifts in biodiversity. Compared to sealing or compaction, alterations related to the addition of nutrients are hardly visible but impact the biocoenosis for long periods. Acidic or basic compounds have less severe effects on the soil habitat, except in the case of long-term inputs.

Airborne inputs and landfilling containing charcoal and combustion residues may also affect soil organic matter, the primary food source for soil organisms. For example, urban dust contains substantial amounts of pyrogenic carbon from incomplete combustion, a refractory fraction of organic C with important implications for various soil biological processes (FERNANDES et al., 2003; SCHMIDT & NOACK, 2000). Several studies on urban soils have reported differing compositions of natural soil organic matter compared to soils without inputs of charcoal and combustion products (BEYER, 1997; SCHLEUSS et al., 1998; WU et al., 1995). Thus, evaluating the habitat function of urban soils must taken into account the potentially altered composition of the soil organic matter (BEYER et al., 2001).

Interferences in the soil water regime have serious consequences for soil organisms. A balanced water regime results in a coenosis shift and a loss of biodiversity. In contrast, altered soil temperatures only rarely have pronounced effects on habitat quality.

The effects of noise and vibrations on soil biocoenose have not been studied so far but might act as stress factors. The consequences of electromagnetic fields and nuclear radiation also remain to be studied. The introduction of exotic species has received little consideration but is a widespread interference in the natural coenosis. Thus, effects of such introductions on soil habitat quality can not be excluded.

When evaluating the habitat quality of soils during planning procedures, reductions in the size of oecotopes should also be considered. Small areas are more susceptible to environmental impacts than large ones.

Despite the lack of detailed studies on the effects of individual activities on soil organisms, some general comments can be given on how human activities pose multiple burdens on soils in urban ecosystems by altering chemical and physical soil properties (MACHULLA, 2000). In early soil development stages, anthropic Regosols normally show low microbial colonization and biomass. Initially, soil development on organic carbon (C_{org})-rich substrates such as sewage sludge and garbage is characterized by high microbial densities. Heavily disturbed soils show reduced

microbial activities, although the activities are still comparable with those in soils used for agricultural purposes.

1.3 Indicators for evaluating suitability of sites for communities of soil microorganisms

Soil microorganisms are a key functional group in the soil environment and their interactions with plants are the basis of all terrestrial ecosystems (SCHLOTER et al., 2003b). Microorganisms control the transformation and mineralization of natural compounds and xenobiotics. Changing environmental conditions rapidly modify the energetic performance and activity rates of the soil microbiota. Soil microorganisms can accomodate environmental constraints due to human activities by adjusting their activity rates, biomass and community structure. These variables are therefore particularly important when the evaluating suitability of sites for soil microorganisms.

Many studies show that microbial biomass and activity closely correlate with soil chemical and physical properties (summarized by MACHULLA, 2000). Highest correlations are reported particularly between biomass carbon (**C_{mic}**) content and **C_{org}**. Microbial biomass or **dehydrogenase** activity show an integrative behavior, while the **C_{mic}-to-C_{org} ratio** is suitable for the clarification of special problems. Nonetheless, routine analyses for evaluating soil microbial habitat quality should restrict themselves to a few, representative, meaningful and reproducible variables. The ideal indicator should work equally well in all environments and reliably reveal which problem existed where. For many soils, microbial biomass is an appropriate indicator due to the very high correlations often observed between microbial biomass and enzyme activities. Individual soil microbiological properties, however, are not useful measures of soil quality because they vary both seasonally and spatially (NANNIPIERI, 1994). Soil microbial communities can be evaluated based on biomass, activity and diversity is reasonable (RÖMBKE et al., 1997). The multitude of microbial components and biochemical pathways therefore makes it unlikely that a sole ideal indicator can be defined based on a single measure. A more appropriate approach would be to use indices based on a combination of different soil properties (TRASAR-CEPADA et al., 1998). Frequently, a minimum data set is applied (CARTER et al., 1997). The appropriate basic indicators and the number of estimated measures are still under discussion. Current national and international programs for monitoring soil quality include biomass, **respiration** measurements, **nitrogen mineralization** and microbial **diversity** (BLOEM et al., 2003). The diversity of the soil microbial community, however, is very difficult to measure, to standardize and to interpret (SCHLOTER et al., 2003a).

1.4 Aim of the study

The aim of this study was the biological and ecotoxicological evaluation of soils in conurbations, considering the city of Stuttgart as an example. Based on soil microbiological analyses and abiotic properties, individual sites are to be classified with respect to their habitat function for microorganisms. This classification is designed to support decisions concerning landuse. The approach involved a close, interdisciplinary collaboration was performed within the BWPLUS Focus “Boden- und Flächenressourcenmanagement in Ballungsräumen“ and the subprojects “Entwicklung von Bewertungssystemen für Bodenressourcen in Ballungsräumen“ (BWPLUS Project BWC 99001: STAHR et al., 2003) and “Entwicklung von Bewertungsrahmen zur Beurteilung der ökosystemaren Potenziale verschiedener Nutzungs- und Strukturtypen im urbanen Bereich“ (BWPLUS Project BWC 99007: RICHTER et al., 2003). Data on soil properties collected by the Institute of Soil Science and on flora collected by the Institute of Landscape and Plant Ecology are incorporated to help evaluate the habitat function. The results of the evaluation should be integrable in the higher-level evaluation of soil ressources in conurbations (BWC 99001).

For this purpose, soil samples were collected repeatedly over 3 years at sites in Stuttgart, and microbial biomass and activity were analyzed by various well-established, simple laboratory methods (SCHINNER et al., 1993). Arylsulphatase, phosphatase and dehydrogenase were selected as possible heavy-metal-sensitive indicators for the ecotoxicological evaluation (ARBEITS-GEMEINSCHAFT ALPEN-ADRIA, 2001; KANDELER et al., 1996; MACHULLA, 2000). Due to poor interpretability, microbial diversity was not investigated (Chapter 1.3). In the course of the study, some simple methods were replaced by DIN ISO standard methods in accordance with new recommendations for the evaluation soil microbiological quality (RÖMBKE & KALSCH, 2000).

A previous soil survey reported the frequent occurrence of charcoal in topsoils in Stuttgart (HOLLAND, 1996). Thus, special attention was given to contributions of combustion-derived carbon (C_{pyr}: pyrogenic carbon) to soil organic matter, the primary food source for soil microorganisms. The microbial data were evaluated with special respect to land use history and soil chemical and physical properties.

2 Study area

2.1 Location

The study area covers the districts Berg, Altstadt and Süd within the city of Stuttgart (Figure 1). The sites “Nordbahnhof III”, “Schwefelbrunnen”, “Hospitalhof”, “Allianz” and “Pfaffenweg” are located in a 1 km wide and 20 km long transect from the joint research with the Institute of Soil Science and the Institute of Landscape and Plant Ecology. The elevation of individual sites ranges from 230 m a.s.l. in the Neckar basin up to 310 m a.s.l. at the southern edge. Furthermore, the sites “Pfarreigarten”, “Kleingarten”, “Kinderheim”, “Klingenbachpark” and “Bergstraße” in Stuttgart-Gaisburg at the eastern edge of the Neckar valley outside of the transect were also studied. The elevation here ranges from 230 to 280 m a.s.l. (MAURER, 2001).

2.2 Climate

Stuttgart is located in the maritime-western Europe clime characterized by relatively warm summer periods and mild winters. The mean annual temperature in the basin is +10 °C, reaching maxima during June, July and August and minima during December, January and February (NACHBARSCHAFTSVERBAND STUTTGART, 1992). For the period 1951-1980, the mean annual precipitation was 679 mm for the station “Stuttgart-Stadtmitte”, while 663 mm were recorded at the station “Stuttgart-Hohenheim” (WWW.STADTKLIMA.DE).

Table 1: Temperature and precipitation at the meterological stations “Stuttgart-Stadtmitte” (250 m a.s.l.) and “Stuttgart-Hohenheim” (420 m a.s.l.) in the study period (WWW.STADTKLIMA.DE; nd = not determined).

Year	Mean annual temperature (°C)		Annual precipitation (mm)	
	Stadtmitte	Hohenheim	Stadtmitte	Hohenheim
2000	12.2	10.8	nd	708
2001	11.7	10.1	nd	821
2002	12.0	10.3	776	1025

The study period was characterized by higher temperatures and, especially in 2002, by a higher precipitation compared to the long-term means (Tab. 1).

2.3 Soils

The area of Stuttgart located in the centre of the south German “Schichtstufenland”, has a high diversity of soil-forming bedrocks. Natural soil formations in the study area are “Braunerde-Pelosole” and “Pelosol-Braunerden” overlying “Keupermergel”; this is accompanied by “Parabraunerden”, “Braunerde-Pelosole” and deep “Kolluvien” at the slopes of the “Keuper”.

Pronounced anthropogenic disturbance within the city resulted in the formation of “Pararendzinen” with diverse features, depending on the paticular land use. Soils in public parks are mainly heaped “Schichtallosol-“ and “Schichtphyrosol-Pararendzinen” from natural substrates frequently containing debris and building rubble in the former and high cover sheets overlying industrial waste in the latter. Natural soils can be found in housing areas, whereby the topsoils are partially disturbed by a long gardening history and enriched with humus up to “Mehrschichtallosol-“ and “Mehrschichtphyrosol-Pararendzinen” developed from rubbish and technogenic substrates in the high-density inner city areas. Small surface areas also contain “Schichttechnosol-Pararendzinen” from technogenic substrates. Soils in railway areas are enriched with humic compounds and soil skeleton due to the construction of the railway tracks. “Mehrschichttechnosol-Lockersyroseme” are typical soil types in these areas.

2.4 Land use

From the northern part of the study area, an old public park stretches to the city centre; to the west this is narrowed by a railway area that also contains apartment and industrial buildings. The building density gradually decreases from the high-density inner city with apartment and commercial buildings to the southern edge of the basin. To the east a typical old landfill (“Gaisburger Bach”) is narrowed by apartment buildings. The landfill is also used as a public park and as allotments.

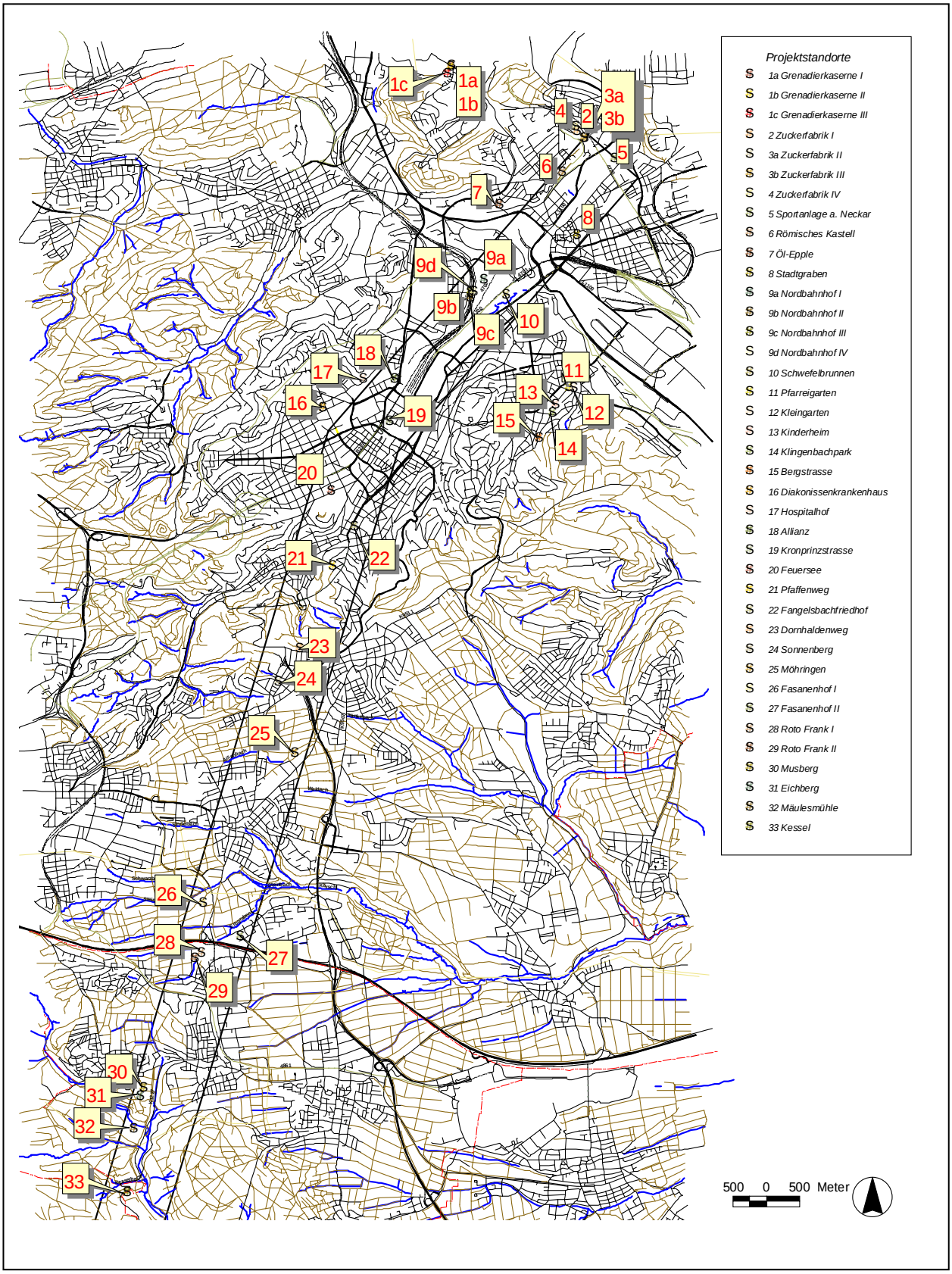

Figure 1: Location of the study sites (see Table 2; STAHR et al., 2003).

3 Material and methods

3.1 Site selection

In collaboration with the Institute of Soil Science (STAHR et al., 2003), soil samples were collected at five types of land use (Tab. 2). To reduce time-consuming and expensive excavation of soil profiles, the range of individual sites depended primarily on the simultaneous soil description and sampling by the subproject. A typical old landfill was also sampled in close collaboration with the institute.

Table 2: Designation of the sites and land use types (RICHTER et al., 2003; STAHR et al., 2003).

Site No.	Name of site	Land use type	Symbol	Soil profile No.	Investigated based on		
					soil science	soil biology	plant ecology
9c	*Nordbahnhof III*	Railway area	**R**	52	x	x	x
10	*Schwefelbrunnen*	Public park	**P3**	54	x	x	
11	*Pfarreigarten*	Allotment	**G2**	48	x	x	
12	*Kleingarten*	Allotment	**G1**	46	x	x	x
13	*Kinderheim*	Public park	**P1**	47	x	x	
14	*Klingenbachpark*	Public park	**P2**	44	x	x	x
15	*Bergstraße*	High-density area	**H1**	45	x	x	
17	*Hospitalhof*	High-density area	**H3**	61	x	x	
18	*Allianz*	High-density area	**H2**	92	x	x	
21	*Pfaffenweg*	Apartment building	**A**	49	x	x	x

Land use functions are a dominant factor for soil development in urban areas (BURGHARDT, 1994). The definition of land use types is therefore crucial for the survey, description and evaluation of attributes and characteristics of urban soils. Five land use types with similar properties were chosen and characterized based on soil microbiological methods (Tab. 3).

Table 3: Typical effects of land use on soil properties (STAHR et al., 2003, modified).

Land use type	Soil type	Effects
Railway area	*Schichttechnosol-Lockersyrosem*	Enrichment of soil skeleton due to consolidation for railway tracks, addition of ash, low in humus, enrichment of pollutants
Apartment building	*Schichtallosol-Pararendzina*	Topsoil disturbed, frequently enriched with humus, mostly semi-natural soils
High-density area	*Mehrschichtphyrosol-Pararendzina*	Partly very old deposited soils from civilization debris (slag, ash, building rubble) coated with natural substrates, highly compressed topsoils, enrichment of soil skeleton in deeper horizons, enrichment of pollutants, underground frequently sealed, highly sealed surface (76-100%)
Public park	*Allosol- and Phyrosol-Pararendzina*	Tipped soils, frequently wreckages and building rubble, enrichment of carbonates and raised pH, sometimes weakly acidified topsoils, enrichment of nutrients and pollutants
Allotment	*Hortisol*	Accumulation and mixture with humus, raised pH, increased contents of nutrients and pollutants

3.2 Soil profiles

The soil profiles were excavated in the autumn 2000. Profile descriptions follow the instructions for surveying and mapping of soils (KA4) from the geological state office (AG BODEN, 1994) and the recommendations by the research group urban soils from the German Soil Science Society (AK STADTBÖDEN, 1997), the latter also serving as the basis for soil classification (Tab. 4). Based on the soil map of Stuttgart, however, the extended classification of HOLLAND (1996) was used by incorporating the amount of technogenic substrates and the stratification into the nomenclature. The methods used for the determination of soil characteristics are summarized in STAHR et al. (2003).

Soil characteristics of the ten study sites are shown in Table 4, with designations following Table 2. The site vegetation data from “Nordbahnhof III”, “Pfaffenweg”, “Klingenbachpark” and “Kleingarten” are completed by descriptions of GRUNICKE et al. (2002) and RICHTER et al. (2003). Additional soil data can be found in Table S1 and elsewhere (HINRICHS, 2001; MAURER, 2001; STAHR et al., 2003).

Table 4: Soil characteristics of the ten study sites.

The available water capacity (AWC) includes pore sizes between 0.2 and 50 µm. The texture classes are sand (2-0.063 mm), silt (63-2 µm) and clay (<2 µm). Estimation of C_{pyr} see Chapter 3.3.3.

The classes are the following:

AWC: <60 very low, 60-140 low, 140-220 medium, 220-300 high, >300 very high

C_{org}: <1 very low, 1-2.5 low, 2.5-5 medium, 5-10 high, >10 very high

N_t: <0.1 very low, 0.1-0.25 low, 0.25-0.5 medium, 0.5-1 high, >1 very high

nd = not determined

Horizon	**Depth**	**Sand**	**Silt**	**Clay**	**Coarse fraction**	**BD**	**C_t**	**C_{pyr}+ C_{org}**	**N_t**	**(C_{pyr}+ C_{org})/ N_t**	**$CaCO_3$**	**pH**		**pCEC**
	(cm)		(%)		(%)	(g cm^{-3})		(%)			(%)	$CaCl_2$	H_2O	(mmol kg^{-1})
R **Site 9c** ***Nordbahn-hof III***	Vegetation: sparse ruderal vegetation, indicators for N and lime, no indicators for drought despite high skeleton content						AWC (l m^{-2} m^{-1}): n.d. C_{org} (kg m^{-2} m^{-1}): 10.1 (very high) N_t (kg m^{-2} m^{-1}): 0.21 (low)							
Profile 52	Substrate: technogenic substrates on slope debris													
yAi	-8	82	16	2	30	1.18	1.4	1.1	0.04	28	0.8	6.9	7.9	29
II yjxC	-25	48	31	21	64	1.00	11.3	11.3	0.24	48	7.7	7.3	8.1	159
III yjxC	-50(1)	30	34	36	47	1.00	4.5	3.2	0.09	36	7.1	7.4	8.1	258
IV yjxC	-50(2)	48	32	20	75	1.00	9.4	8.2	0.13	63	16.3	7.7	8.3	173
IV yjxC	-78	50	29	21	76	1.61	17.8	13.4	0.28	47	13.4	7.6	8.3	186
A **Site 21** ***Pfaffenweg***	Vegetation: garden with solitary walnut, cherry, ash and shrubs						AWC (l m^{-2} m^{-1}): 86 (low) C_{org} (kg m^{-2} m^{-1}): 1.4 (low) N_t (kg m^{-2} m^{-1}): 0.51 (high)							
Profile 49	Substrate: deposited natural substrates													
jAh	-10	51	29	20	15	0.90	4.1	3.4	0.26	13	7.4	6.8	7.3	271
yjC1	-65	23	41	36	12	1.50	1.0	0.2	0.09	2	5.1	7.2	7.5	249
yjC2	-100	23	43	34	11	1.50	1.1	0.2	0.08	2	7.3	7.3	7.6	232

Table 4: continued

Horizon	Depth	Sand	Silt	Clay	Coarse fraction	BD	C_t	$C_{pyr}+C_{org}$	N_t	$(C_{pyr}+C_{org})/N_t$	$CaCO_3$	pH		pCEC
	(cm)		(%)		(%)	(g cm^{-3})		(%)			(%)	$CaCl_2$	H_2O	(mmol kg^{-1})
H1	Vegetation: ruderal vegetation, indicators for N and lime,						AWC (l m^{-2} m^{-1}): 76 (low)							
Site 15	public park after sowing white glover-ryegrass in autumn						C_{org} (kg m^{-2} m^{-1}): 3.5 (medium)							
Bergstraße	2002						N_t (kg m^{-2} m^{-1}): 0.21 (low)							
Profile 45	Substrate: tipped natural substrates with rubble from buildings and coal, 15 years old													
jAh	-6	33	42	25	8	0.90	5.7	3.7	0.26	14	16.5	6.6	7.2	293
jAh-jC	-20	33	45	22	24	1.20	4.9	2.8	0.19	15	17.3	6.7	7.4	268
II jyxC	-35	90	7	3	68	0.80	0.7	0.2	0.02	9	4.7	7.1	7.9	42
III jC	-75	47	31	22	21	1.63	2.1	1.1	0.07	16	7.1	7.1	8.0	278
III yjC														
IV yxC	-155	nd	nd	nd	84	1.70	4.7	3.1	0.13	24	13.4	7.2	7.9	268
V yC	-170	40	39	21	33	1.30	6.5	5.3	0.16	33	10.0	7.2	7.9	305
VI ylC	-190	52	32	16	50	0.95	36.7	35.9	0.65	55	6.1	6.8	7.3	640
H2	Vegetation: park with solitary broad-leafed trees and						AWC (l m^{-2} m^{-1}): 85 (low)							
Site 18	shrubs						C_{org} (kg m^{-2} m^{-1}): 3.3 (medium)							
Allianz							N_t (kg m^{-2} m^{-1}): 0.34 (medium)							
Profile 92	Substrate: Gipskeuper buried by deposited natural substrates													
yjAh	-9	33	38	28	24	1.29	8.0	7.1	0.32	22	7.4	7.2	7.3	302
II yjC	-40	5	58	37	6	1.46	1.0	1.5	0.16	10	1.2	7.1	7.9	304
III C	-60	15	41	44	29	1.48	3.2	0.9	0.09	10	19.7	7.3	8.2	268
IV C	-100	8	42	50	56	1.64	3.9	0.3	0.06	5	29.8	7.4	8.3	278
H3	Vegetation: park with rhododendron						AWC (l m^{-2} m^{-1}): 112 (low)							
Site 17							C_{org} (kg m^{-2} m^{-1}): 2.3 (low)							
Hospitalhof							N_t (kg m^{-2} m^{-1}): 0.32 (medium)							
Profile 61	Substrate: deposited natural substrates													
yjAh	-6	31	36	33	8	1.47	3.8	3.2	0.30	11	5.4	6.8	7.2	318
II jAhCv	-25	25	39	36	10	1.56	2.0	1.4	0.14	10	4.6	7.2	7.8	268
III yjC	-43	14	47	39	15	1.66	2.2	1.3	0.06	21	7.4	7.5	8.1	258
IV yjC	-80	11	56	33	3	1.71	2.2	0.2	0.06	4	16.5	7.6	8.2	205

Table 4: continued

Horizon	Depth	Sand	Silt	Clay	Coarse fraction	BD	C_t	$C_{pyr}+C_{org}$	N_t	$(C_{pyr}+C_{org})/N_t$	$CaCO_3$	pH		pCEC
	(cm)		(%)		(%)	(g cm^{-3})		(%)			(%)	$CaCl_2$	H_2O	(mmol kg^{-1})
P1	Vegetation: park with white glover-ryegrass and broad-leafed tree rows						AWC (l m^{-2} m^{-1}): 88 (low)							
Site 13 ***Kinderheim***							C_{org} (kg m^{-2} m^{-1}): 2.2 (low)							
							N_t (kg m^{-2} m^{-1}): 0.22 (low)							
Profile 47	Substrate: natural loam tipped on natural soil													
jAh-C	-8	17	45	38	2	1.74	2.8	1.1	0.11	10	14.0	7.3	7.7	317
jC	-29	22	44	34	4	1.71	2.1	0.6	0.06	9	12.6	7.3	7.6	304
yjC/II fAh	-52	14	42	44	1	1.60	1.0	0.6	0.07	9	3.0	7.3	7.5	313
II fAh	-76	10	36	54	0	1.64	0.8	0.7	0.06	12	0.2	7.2	7.3	459
II P	-100	18	39	43	0	1.74	0.5	0.4	0.05	9	0.5	7.2	7.4	294
II p-Cv	-144	23	40	37	0	1.70	0.8	0.2	0.03	6	4.7	7.4	7.5	266
II Cv	-150	23	42	35	3	nd	0.9	0.2	0.07	3	5.8	7.5	8.1	244
P2	Vegetation: park with white glover-ryegrass, nearby dense stock of trees and shrubs						AWC (l m^{-2} m^{-1}): 145 (medium)							
Site 14 ***Klingen-bachpark***							C_{org} (kg m^{-2} m^{-1}): 33.3 (very high)							
							N_t (kg m^{-2} m^{-1}): 0.65 (high)							
Profile 44	Substrate: deposited natural loam on rubbish, building rubble, slag													
jAh	-5	31	44	25	1	0.9	10.6	10.3	0.53	19	2.6	6.8	7.1	396
jAh-C	-25	31	41	28	17	1.32	7.5	6.8	0.31	22	6.0	7.0	7.4	317
II yC1	-80	56	39	5	36	0.70	20.6	19.4	0.32	61	10.2	7.5	7.8	232
II yC2	-160	61	31	8	23	0.71	17.8	16.8	0.30	56	8.0	7.6	7.6	214
P3	Vegetation: park with old sycamore trees and shrubs						AWC (l m^{-2} m^{-1}): 142 (medium)							
Site 10 ***Schwefel-brunnen***							C_{org} (kg m^{-2} m^{-1}): 3.6 (medium)							
							N_t (kg m^{-2} m^{-1}): 0.32 (medium)							
Profile 54	Substrate:deposited natural substrates													
yjAh	-18	39	29	32	14	1.06	6.1	5.4	0.40	14	5.5	7.0	7.3	391
yjAh/Cv	-40	24	38	38	7	1.30	2.8	1.7	0.17	10	8.5	7.3	7.8	281
II yjC	-71	20	48	32	11	1.59	3.2	1.6	0.17	10	13.3	7.3	7.9	253
III jC	-95	22	43	35	6	1.48	3.0	1.2	0.12	10	15.1	7.5	8.1	233
IV jC	-120	11	53	36	8	1.42	1.8	0.4	0.09	5	11.2	7.7	8.3	261

Table 4: continued

Horizon	Depth	Sand	Silt	Clay	Coarse fraction	BD	C_t	$C_{pyr}+C_{org}$	N_t	$(C_{pyr}+C_{org})/N_t$	$CaCO_3$	pH		pCEC
	(cm)		(%)		(%)	(g cm^{-3})		(%)			(%)	$CaCl_2$	H_2O	(mmol kg^{-1})
G1	Vegetation: stinging nettle, ivy, broad-leafed trees, hedgerow						AWC (l m^{-2} m^{-1}): 91 (low)							
Site 12 ***Kleingarten***							C_{org} (kg m^{-2} m^{-1}): 10.4 (very high)							
							N_t (kg m^{-2} m^{-1}): 0.46 (medium)							
Profile 46	Substrate: compost, rubbish, building rubble													
jyxC-Aa	-25	38	37	25	67	0.9	11.9	10.8	0.72	15	9.2	6.8	7.1	503
jyxC	-60	37	40	23	57	1.0	8.9	7.2	0.33	22	14.1	6.9	7.4	356
II jC1	-90	35	41	24	21	1.33	6.1	4.3	0.15	29	14.8	7.1	7.7	254
II jC2	-110	37	39	24	34	1.29	9.1	7.2	0.14	51	16.1	7.3	7.9	210
II jC3	-120	37	42	21	29	1.42	10.4	8.4	0.15	56	16.6	7.5	8.4	188
III jC	-155	35	43	22	38	1.56	4.8	2.8	0.07	40	16.5	7.7	8.5	180
G2	Vegetation: lawn, red currant, fruit trees						AWC (l m^{-2} m^{-1}): 272 (high)							
Site 11 ***Pfarrei-garten***							C_{org} (kg m^{-2} m^{-1}): 3.2 (medium)							
							N_t (kg m^{-2} m^{-1}): 0.35 (medium)							
Profile 48	Substrate: deposited natural substrates on loess loam													
jAh	-6	12	48	40	0	0.9	5.3	4.0	0.34	12	10.0	6.7	7.0	395
jAh-C	-16	12	46	42	0	1.43	4.2	2.8	0.23	12	11.4	6.9	7.2	345
II jC	-50	19	43	38	0	1.47	2.4	1.0	0.09	11	12.3	7.1	7.6	298
III Cv	-110	11	64	25	0	1.58	3.2	0.3	0.04	7	23.8	7.4	7.8	219

The soil in the railway area “Nordbahnof III”, disused since several years, developed from technogenic substrates on slope debris (Tab. 4). The soil reacts alkaline. The topsoil is poor in carbonates, sandy, with a very low compaction and a single-grained structure. By contrast, the subsoil is very calcareous to carbonate rich, loamy, shows medium to high compaction and varying structures. Striking features of this soil are high contents of the coarse fraction and very high amounts of C_{org}. Concomitant low amounts of N_t and high C-to-N ratios indicate the enrichment by technogenic substrates high in pyrogenic/lithogenic C. Because of a high skeleton content, the soil demonstrates favorable rootability in the upper part of the soil profile and low rootability below. Plant growth is hampered by low organic matter content and medium nutrient availability, as indicated by the potential cation exchange capacity in the topsoil. A restricted water supply during summer, along with pollutants from technogenic substrates and railway

operations, might also hamper plant growth (STAHR et al., 2003). The available water capacity was not determined. The base of the railway tracks is made of gravel and contains C-rich ash, coal and coke, contributing to high C contents and wide C-to-N ratios. A sulfide smell indicates temporary anaerobic conditions due to high water tables, but redoximorphic features have not developed (STAHR et al., 2003). In summary, a “Mehrschichttechnosol-Lockersyrosem” has formed.

Natural substrates are the parent material of the soil profile 49 (“Pfaffenweg”) located in a house garden surrounding an apartment built in 1900. For gardening, a natural A_h-horizon was mixed with crushed bricks and sandstones. The soil reacts alkaline and is very high in carbonates. The texture is loamy and the structure is characterized as subangular blocky. The topsoil is very humic and has a very low bulk density. Together with a medium potential CEC, this promotes the growth of fruit trees and numerous earthworms. By contrast, the subsoil is very weakly humic and densified. The soil profile shows a medium rootability and a low available water capacity. High amounts of total nitrogen were detected. A “Schichtallosol-Pararendzina” has formed.

The soil at the site “Bergstraße” shows very heterogeneous soil chemical and physical properties because natural substrates mixed with technogenic substrates were tipped several times since the Second World War (Fig. 2). Different kinds of rubble (glass, plastics, concrete, bricks, slag, ash, bones) were buried in the soil and, after 1985, covered by a loamy substrate to support vegetation growth. The topsoil is slightly acidified compared to the subsoil. The humus content is high in the upper and very high in the lower part of the profile but very low in between. Coal particles are visible in the entire profile and, below 75 cm, the wide C-to-N ratios indicate high amounts of pyrogenic/lithogenic C. The low bulk density between 170 and 190 cm compared with overlying horizons corresponds with the porous structure of combustion-derived carbon. This horizon also shows a high nutrient availability, whereas the other horizons had a medium nutrient availability. Rootability is favored in the upper part of the soil profile but hampered below, probably due to a low available water capacity as a consequence of high stone contents. The soil type is a “Mehrschichtphyrosol-Pararendzina”. In autumn 2002, the topsoil was mixed with a natural A_h-horizon and homogenized, and the ruderal vegetation was substituted by white glover-ryegrass.

Figure 2: Soil profiles at “Bergstraße”, “Klingenbachpark” and “Pfarreigarten” (left to right, decreasing anthropogenic disturbance).

The soil profile 92 at “Allianz” derived from natural substrates on clay-rich “Gipskeuper” and is located in a court-yard of a high-density area built around 1900. Natural substrates high in carbonates and skeleton, frequently containing coal, were mixed and deposited on a natural soil. With increasing depth, carbonate and skeleton contents increase drastically, whereas the soil reaction remains alkaline. The topsoil is humic, supports many earthworms and is heavily rooted by solitary trees and shrubs. The humus content strongly decreases with depth. The subsoil demonstrates very low rootability due to strong compactness. The available water capacity for the soil profile is low, and the soil shows medium N_t amounts and nutrient availability. The texture is mainly subangular blocky. In summary, a “Mehrschichtallosol-Pararendzina” has formed.

Soil profile 61 at “Hospitalhof” is located in a 40-years-old court-yard covering an underground car park in a high-density area. Natural substrates were mixed with rubble for reclaimed land, now promoting growth of a green space with rhododendron. The soil texture varies in the entire profile. The uppermost layer reacts almost neutrally, is very humic and heavily rooted with a high earthworm density. Down to 43 cm the soil is weakly humic and the coarse fraction and alkalinity increase while carbonate contents vary. Charcoal contributes to the wide C-to-N ratios between 25 and 43 cm. Below 43 cm, the skeleton and humus content is very low and the carbonate content strongly increases until the drainage layer (80 - 95 cm). The soil profile shows

a low available water capacity, medium N_t amounts and medium nutrient availability. Rootability in the upper part is favorable, but compactness restricts rootability in the lower part. The soil is described as a “Mehrschichtallosol-Pararendzina”.

Two very homogeneous layers characterize soil 47, which is located in the park area “Kinderheim” covered by white clover-ryegrass. The topsoil is a landfill consisting of calcareous loam mixed with rubble deposited on an old “Pelosol” developed from “Keupermergel”. Humus accumulated only in the top layer, while deeper horizons are low in humus. The soil profile contains very few coarse fragments, the soil reacts alkaline and the carbonate content strongly decreases with depth. High compactness and low available water capacity hampers rootability despite medium to high nutrient availability. The soil texture is mainly blocky. A “Mehrschicht-allosol-Pararendzina” has formed.

Soil 44 at “Klingenbachpark” consists of natural loamy substrates tipped on two layers of sandy slag (Fig. 2). Landfilling of debris from tunnel excavations and debris from the Second World War contributed to the high content of the technogenic coarse fraction in the profile. In 1960 a park with white clover-ryegrass was created. Striking features of the soil profile are very high amounts of C_{org}. However, coal components are visible down to 80 cm and pyrogenic/lithogenic C contributes to the increasing C-to-N ratios with depth. The top layer is slightly acidified and low in the coarse fraction, while alkalinity and soil skeleton increase with depth. The soil texture is variable. The soil is deeply rooted due to low compactness and demonstrates favorable available water capacity and nutrient availability. The soil type was described as “Schichttechnosol-Pararendzina”.

A landfill composed of natural substrates is the parent material for soil profile 54 at “Schwefelbrunnen”, covered by a park with old trees and shrubs. The soil is low in stone content and reacts alkaline. The top layer is very humic, low in carbonates and has a high earthworm density. Carbonate contents increase with depth, while humus contents decrease. The soil texture is highly variable. The soil demonstrates favorable rootability in the upper part of the soil profile and low rootability below due to increasing compactness. Nutrient availability for the soil profile is medium. A “Mehrschichtallosol-Pararendzina” has formed.

Soil 46 at “Kleingarten”, covered by nutrient-rich vegetation, is located beside a frequently used compost area surrounded by allotments build after the Second World War. The main features are very high contents of the coarse fraction in the topsoil (containing rubble and construction waste) and very high C_{org} amounts and carbonate contents in the soil profile. Coal and coke pieces are clearly visible, both contributing to wide C-to-N ratios. The soil texture is mainly subangular blocky. The topsoil reacts alkaline and alkalinity increases with depth. Very high humus contents in the uppermost layer, together with high contents of the coarse fraction and a

high potential CEC, promote rootability. By contrast, rootability below is medium due to lower humus and stone contents. A “Schichtphyrosol-Pararendzina” has formed.

The top and base of soil profile 48 at “Pfarreigarten” are very homogeneous, whereas the soil is heterogeneous in between. In this lawn with shrubs and fruit trees, natural substrates were tipped on a loess loam. Striking features are a very low skeleton content and a high available water capacity. The topsoil is humic, high in carbonates, slightly acidic and contains many roots and earthworms. With increasing depth the humus content strongly decreases while carbonate content and alkalinity increase. Although compactness increases with depth, rootability decreases. The medium potential CEC for the soil profile indicates favorable nutrient availability. In total, a “Schichtallosol-Pararendzina” has formed.

3.3 Soil analysis

3.3.1 Soil sampling

In arable, grassland and forest soils, almost 90 % of the microbial biomass is located in the upper 30 cm of the soil (MACHULLA, 2000). Evaluations of soil quality and habitat function thus focus on topsoil samples (e.g. MACHULLA et al., 2001; OBERHOLZER et al., 1999; SOMMER et al., 2002). In order to enhance the statistical validity of the microbial variables and to reduce time-consuming and expensive determinations of belowground variables, the soil microbial measurements taken here and covering three vegetation periods were restricted to topsoil samples collected at the urban sites.

In autumn 2000, three samples from each soil horizon at the ten profiles were taken using a spade (Tab. 6). Repeated topsoil sampling was done near the profiles in autumn 2001 and 2002. Three random samples of the uppermost soil horizon were collected by excavating small soil pits with a spade. Two samples (core diameter 50 mm) from the subsequent horizon at each soil pit were taken and combined. After the removal of green plant material and roots, samples were sieved (mesh size < 5 mm) and stored in plastic bags at –20 °C. Two days prior to microbial measurements, samples were deiced in a fridge (4 °C). In total, 9 samples from the two uppermost topsoil horizons at each site were characterized by soil microbial methods.

3.3.2 Heavy metals

The concentrations of heavy metals in individual horizons of the ten soil profiles were determined by ICP after aqua regia extraction by the Regional Institute of Agricultural Chemistry ("LA Chemie"; Tab. 5; STAHR et al., 2003). In addition, for ecotoxicological evaluation mobile fractions were determined by ICP by the instiute of Soil Science and the Regional Institute of Agricultural Chemistry according to the Federal Soil Protection Ordinance (BBodSchV) after extraction with NH_4NO_3 (data not shown).

Based on the background levels for rural areas in Baden-Württemberg, the heavy metal loads of the respective soils differ (Tab. 5). Soil profiles at P1 and P3 (park soils) and G2 (garden soil) are very low in heavy metals, mainly due to elevated contents of the parent material e.g. "Oberer Muschelkalk" (MINISTERIUM FÜR UMWELT UND VERKEHR BADEN-WÜRTTEMBERG, 1999). Differences in land use history, especially devastations during the Second World War, are mainly responsible for elevated heavy metal contents in the other soil profiles. Domestic fuelling, industry and traffic in Stuttgart result in nonpoint airborne soil pollution with heavy metals. The substrate for building the railway tracks and airborne inputs during railway operations are mainly responsible for the high contents of Cu, Pb and Zn at "Nordbahnhof III", frequently exceeding precaution values. Urban dust and gardening contribute to the high Pb and Zn contents in the top layer in the garden at the apartment building "Pfaffenweg", which is located at a higher elevation than the city centre. At this site, precaution values for clayey soils are exceeded for Pb and Zn. Burying of rubble resulted in high Cu, Pb and Zn contents at the landfill site "Bergstraße" (H1). Copper and Zn levels in the subsoil exceed the precaution values. Landfilling and immision of urban dust also contribute to elevated Cu, Pb and Zn levels of the soil profile at H2 in the city centre, exceeding precaution values in the topsoil for Cu and Pb. The same sources are responsible for elevated Pb and Zn levels of the soil profile at "Hospitalhof" (H3), also located in the city centre. The landfill body of the profile at P2 is problematical because it exceeds the precaution values for Cd, Cu, Pb and Zn in the entire profile. Furthermore, the test value for playgrounds is exceeded for Pb. Composting of plant-garbage mixtures and landfilling contributes to high Cd, Cu, Pb and Zn levels in the soil profile of the "Kleingarten" (G1). With the exception of Cu, threshold values are exceeded.

Table 5: Heavy metal concentrations (aqua regia extraction) in the soil profiles (mg kg^{-1}).

Depth (cm)	Cd	Cr	Cu	Ni	Pb	Zn
R: *Nordbahnhof III*						
-8	0.2	29	56	67	30	145
-25	0.8	63	85	41	171	285
-50(1)	0.2	37	30	33	64	142
-50(2)	0.5	32	287	39	180	322
-78	0.4	39	112	40	297	290
A: *Pfaffenweg*						
-10	0.5	37	23	22	283	553
-65	0	52	10	31	24	91
-100	0	52	9	32	24	91
H1: *Bergstraße*						
-6	1.0	52	46	31	42	202
-20	1.1	55	47	30	41	200
-35	0.3	14	20	10	16	89
-75	0.8	40	221	29	79	524
-155	0.8	30	264	25	169	608
-170	0.7	38	118	28	134	327
-190	0.7	24	44	21	86	161
H2: *Allianz*						
-9	1.0	66	137	50	242	379
-40	0.3	68	43	46	92	141
-60	0.2	65	55	65	107	184
-10	0	44	12	30	16	64

Table 5: continued

Depth (cm)	Cd	Cr	Cu	Ni	Pb	Zn
H3: *Hospitalhof*						
-6	0.9	68	52	43	91	242
-25	0.6	67	43	43	63	228
-43	0.2	64	21	43	27	105
-80	0.1	45	18	37	15	69
P1: *Kinderheim*						
-8	0.2	45	21	30	20	64
-25	0.2	43	19	31	15	58
-52	0.2	41	17	29	18	57
-76	0.2	47	15	30	14	59
-100	0.2	38	12	27	16	54
-144	0.2	40	11	29	14	53
-150	0.2	45	12	29	14	54
P2: *Klingenbachpark*						
-5	0.9	37	182	39	313	483
-25	0.8	41	124	38	248	396
-80	1.7	69	442	101	827	1087
-160	1.6	44	475	63	304	623
P3: *Schwefelbrunnen*						
-18	0.4	46	29	30	44	109
-40	0.3	52	40	36	44	162
-71	0.4	40	35	32	59	142
-95	0.2	36	26	30	39	72
-120	0.2	54	20	36	24	67

Table 5: continued

Depth (cm)	Cd	Cr	Cu	Ni	Pb	Zn

G1: *Kleingarten*						
-25	1.2	60	91	35	134	538
-60	1.1	52	60	32	125	484
-90	0.8	43	52	37	101	473
-110	0.5	40	43	34	58	211
-120	0.4	30	30	29	37	123
-155	0.3	26	19	23	43	55
G2: *Pfarreigarten*						
-6	0.4	46	36	35	50	120
-16	0.4	43	35	33	72	97
-50	0.3	47	29	34	29	68
-110	0.3	39	14	28	13	52
Background values for rural areas in Baden-Württemberg (UMWELTMINISTERIUM BADEN-WÜRTTEMBERG, 1993)						
	0.2-1.0	20-90	10-60	35-150	25-55	35-150
Precaution values according to the German Soil Protection Ordinance (BUNDES-MINISTERIUM FÜR UMWELT, NATURSCHUTZ UND REAKTORSICHERHEIT, 1999)						
Clay	1.5	100	60	70	100	200
Loam/Silt	1.0	60	40	50	70	150
Sand	0.4	30	20	15	40	60

3.3.3 Soil organic matter quality

Contributions of combustion-derived organic carbon, e.g. from charcoal and soot, to soil organic matter (SOM) were evaluated by estimating C_{pyr}. Pyrogenic carbon in the soil profiles was estimated by a modified method for soot carbon described by GUSTAFSSON et al. (1997). The approach is based on thermal oxidation of the organic carbon (C_{org}). Organic C was removed by oxidizing 0.5 g air-dried and finely-ground soil at 375 °C for 24 h in the presence of excess air, leaving C_{pyr} and carbonates behind. Before and after oxidation, inorganic carbon in carbonates

was determined via acidification using a Wösthoff apparatus. The C composition of the samples before and after heating was determined using a Leco CN analyzer. Pyrogenic C was calculated by subtracting the difference between C_t and inorganic C after heating from the difference between both before thermal oxidation:

$$\mathbf{C_{pyr} = C_t - C_{carbonate} - C_t\ (24h,\ 375\ °C) - C_{carbonate}\ (24h,\ 375\ °C)}$$

SOM quality was characterized in finely-ground, dried soil samples by solid-state ^{13}C NMR spectroscopy with cross-polarization and magic-angle spinning (CPMAS) with a Bruker MSL 300 spectrometer operating at 75 MHz. A 7 mm rotor at 4700 Hz MAS or a 4 mm rotor at 8000 Hz was used; background subtraction was done if required. Some quantitative Bloch decay (BD) spectra with 100 s recycle time were also run. Spectra were divided into the following chemical-shift regions for C: alkyl (0-50 ppm), O-alkyl (50-110 ppm), aromatic and phenolic (110-160 ppm), and carboxyl and carbonyl (160-210 ppm). Relative areas were corrected for spinning side bands (SBB) of the carboxyl peak. Signal-to-noise ratios of the spectra were improved by removing paramagnetic iron oxides which selectively quench signal intensity of carbons and by removing silicates to raise organic C using 10 % hydrofluoric acid (SCHMIDT et al., 1997).

3.3.4 Microbial characterization

Before beginning routine analysis, the suitability of well-established methods for characterizing microbial biomass and activity in selected urban soils from Stuttgart was tested. The methods included analysis of phospholipid fatty acid patterns for microbial biomass, determination of ergosterol content for fungal biomass, and determination the activities of invertase, xylanase and protease. A preselection of methods was necessary to reduce the effort for routine analysis. This was done against the background of possible effects of heavy metals on soil microorganisms because data were also collected on heavy metals in the studied urban soils (STAHR et al., 2003). As a result, chloroform fumigation extraction and substrate-induced respiration were chosen to determine microbial biomass (Chapter 3.3.4.1). Microbial activity was characterized by determinating dehydrogenase, urease, arylsulphatase and anaerobic N-mineralization (Chapter 3.3.4.2). This set of variables was modified in 2001 according to recommendations for characterizing soil microbiological quality proposed by an international roundtable (RÖMBKE & KALSCH, 2000). The recommendations included DIN / ISO standard methods, aerobic instead of anaerobic N-mineralization and potential ammonia oxidation. In total, two recommended methods for biomass and three recommended for activity were applied; this was

complemented by determination of potentially heavy-metal-sensitive enzyme activities (arylsulphatase, phosphatase, urease).

3.3.4.1 Microbial biomass

Microbial biomass (biomass-C and –N) was determined by the chloroform-fumigation extraction (CFE) method (VANCE et al., 1987), biomass-C also by the substrate-induced respiration (SIR) method (ANDERSON & DOMSCH, 1978). Since 2001, standard methods for CFE (DIN ISO 14240-2) and SIR (DIN ISO 14240-1) were used.

3.3.4.2 Microbial activity

Microbial activity was characterized by determining dehydrogenase activity using the substrate triphenyltetrazoliumchloride (ÖHLINGER, 1993a), since 2001 according to DIN 19733-1. Nitrogen transformation in the soils was characterized by measuring urease activity (KANDELER, 1993a); as of 2001, N-transformation was also characterized by measuring potential ammonium oxidation (ISO CD 15685). Nitrogen mineralization in the samples from the soil profiles was characterized by anaerobic incubation (KANDELER, 1993b). This method was replaced in 2001 by aerobic incubation (DIN ISO 14238). Sulfur transformation was characterized by measuring arylsulphatase activity (STROBL & TRAUNMÜLLER, 1993) and phosphorus transformation, after 2001, by measuring phosphomonoesterase activity at alkaline pH (ÖHLINGER, 1993b).

Table 6: Soil samples for microbial characterization.

Land use type	Symbol	Depth (cm)
Railway area	R	0-8
		8-25
Apartment building	A	0-10
		10-65
High-density area	H1	0-6
		6-25
	H2	0-9
		9-40
	H3	0-6
		6-25
Park area	P1	0-8
		8-29
	P2	0-5
		5-25
	P3	0-18
		18-40
Garden area / allotment	G1	0-25
		25-60
	G2	0-6
		6-16

3.4 Data presentation and statistical analysis

For site comparisons, chemical variables, microbial biomass and activities were calculated for each topsoil horizon and hectare with respect to bulk density and soil skeleton. Based on this calculation the properties of a hypothetical horizon reaching to 30 cm depth were calculated by summarizing. The evaluation of dependencies between abiotic soil properties and microbial variables calculated on an area basis is a relatively new approach (SOMMER et al., 2002). This calculation, however, also supports the ecological evaluation of sites with respect to their potential for disintegrating and buffering inorganic and organic pollutants (MACHULLA, 2000). DORAN & PARKIN (1996) argue strongly for expressing indicators of soil quality volumetrically rather than gravimetrically because this incorporates differences in bulk density. Furthermore, from an ecological point of view there is a demand for a volume-based soil sampling that considers coarse material contents. This facilitates data comparisons from different investigations (SCHLEUSS & MÜLLER, 2001).

The present results are based on arithmetic means (±standard deviation) of 9 samples. Results for NH_4-oxidation, N-mineralization and phosphatase activity are based on 6 samples. For statistical validity of the results, variables were tested for normality (Kolmogorov-Smirnov) and homogeneity of variances (Levene's test). Data were log-transformed prior to analysis. Differences between means were tested by a one-way analysis of variance (ANOVA; $p<0.05$). Pearson correlation coefficients ($p<0.01$) were calculated to detect connectivities between abiotic soil properties and microbial variables. Multiple linear regression analyses were performed to predict microbial variables through abiotic variables.

Pyrogenic C and NMR spectroscopy were carried out on composite samples from individual horizons of the soil profiles and are therefore interpreted qualitatively.

4 Results and discussion

4.1 Soil organic matter

4.1.1 Thermal degradation of soil organic matter

The stocks of soil organic carbon in the top 30 cm of the profiles clearly differed between the sites (Fig. 3, Tab. S1). These differences reflect varying bulk densities and soil skeleton contents along with plant litter inputs and contributions of organic waste. For example, the disposal of garden waste at garden area 1 did not result in high stocks of organic carbon in the topsoil because, concomitantly, coarse particles were also buried. The railway area, however, had comparable stocks despite very sparse vegetation and low skeleton contents; here, contributions from organic contaminants probably played a role. The highest stocks were found at the park area 2, whereas soil organic carbon was very low in the garden of the apartment building and the park area 1.

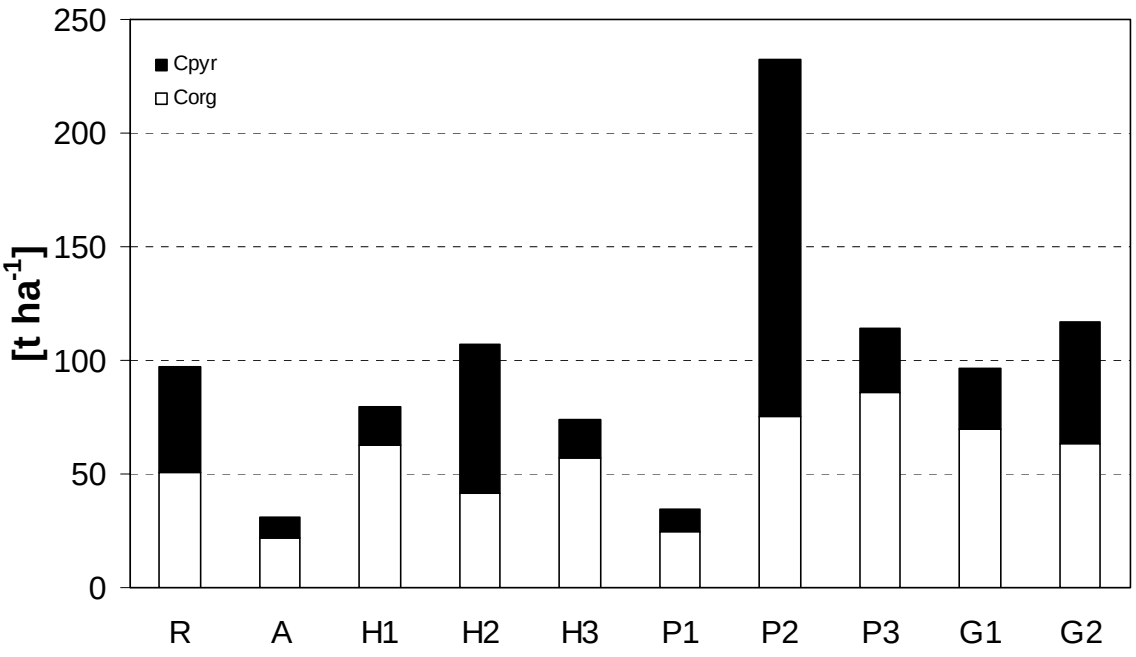

Figure 3: Organic carbon (C_{pyr} + C_{org}) in 0-30 cm depth.

Stocks of pyrogenic C were also highly variable between the sites. This depended on the burial and/or airborne inputs of incompletely combusted organic matter, although differences in bulk densities and soil skeleton also played a role. Park area 2 was very high in C_{pyr}, mainly due to landfilling, with the highest contributions of C_{pyr} to soil organic C (67 % C_{pyr}). Very low stocks were recorded for the remote apartment building and park area 1. High-density area 1 had the lowest contribution of pyrogenic C to soil organic C (22 % C_{pyr}). At most of the sites in Stuttgart, pyrogenic C was visible in the profiles during the soil survey (Chapter 3.2; see also HOLLAND, 1996). Thermal oxidation, however, indicated that the studied urban profiles probably contain C_{pyr} as fine dust, which is impossible to recognize visibly (BEYER et al., 2001).

4.1.2 Soil organic matter quality (^{13}C CPMAS NMR spectroscopy)

NMR spectroscopy is expensive and time consuming. Thus, spectra were obtained only from selected soil samples that were high in organic matter and that promised reliable spectra (Tab. 6). Most spectra were typical for natural soil organic matter derived from plant litter compounds, with high alkyl, O-alkyl, and low aromatic and phenolic C (MAHIEU et al., 1999). Comparable results were obtained for urban soils from Rostock (BEYER et al., 2001). However, sparse plant cover at the railway area was one reason for the missing intensity from plant-derived O-alkyl in the spectra of the topsoil from “Nordbahnhof III”. Topsoil samples from garden areas had stronger phenolic and methoxyl signals, indicating accumulation of lignin, perhaps due to disposal of woody garden waste. Samples from the railway area, high-density area 2, park area 2 and garden area 1 were higher in aromatic C, typical of pyrogenic C (e.g. P2 0-5 cm and 5-25 cm, Fig. 4).

Treatment with HF improved the quality of the cross-polarization (CP) spectra and reduced the need for background subtraction, but it was still difficult to obtain quantitative Bloch decay (BD) spectra, and these did not result in dramatic increases in aromatic C (Tab. 6). For samples high in pyrogenic C, the CP and BD spectra are similar (CZIMCZIK et al., 2002; 2003).

There was a poor correlation between C_{pyr} (as estimated by thermal oxidation) and the percentage of aromatic C as determined by NMR (Fig. 5). The latter is slightly underestimated, especially for the BD spectra, and needs further correction for the spinning sidebands of the aromatic/phenolic region.

The percentage of C detected by NMR, even by BD, remains unknown, but it should be close to 100% for the HF-treated samples.

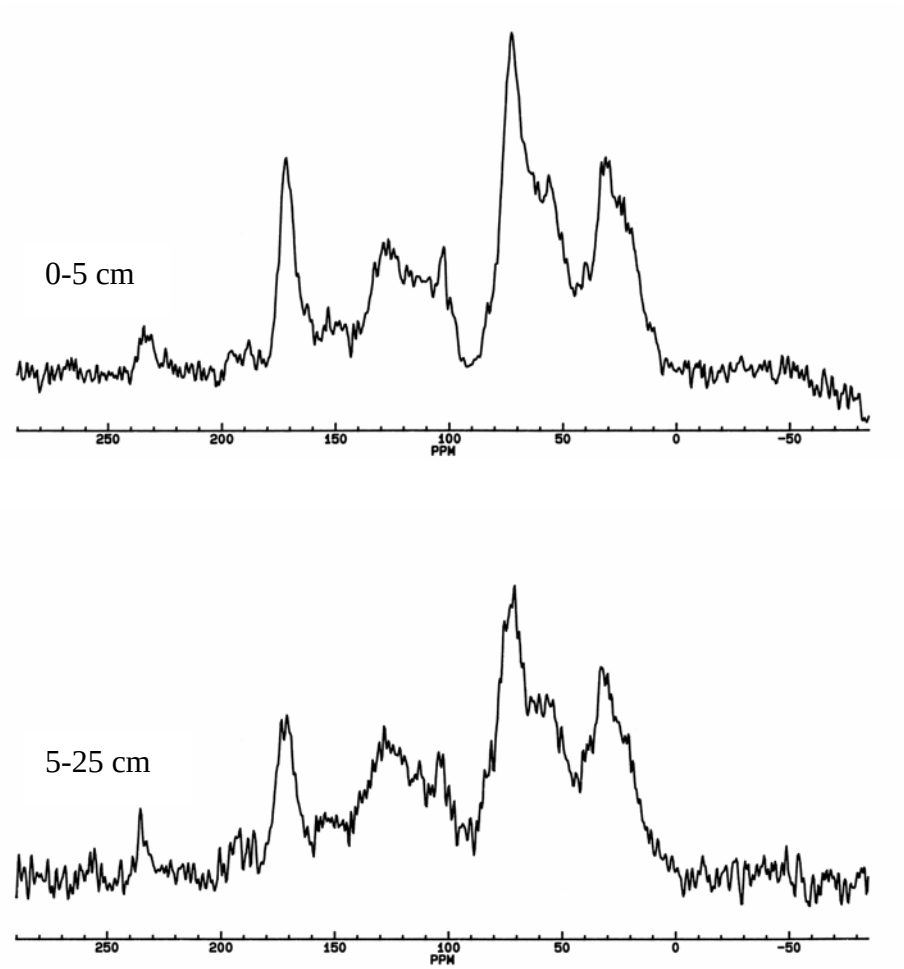

Figure 4: ^{13}C CPMAS NMR spectra of topsoil samples from park area 2.

For samples with C_{pyr} ranging from 22-67 % of non-carbonate C, NMR aromatic C for most samples only ranged between 14-33 %. Of the samples with very high aromatic C, two had correspondingly high pyrogenic C, but the other had only 48 %. In a previous study, pyrogenic C based on NMR was around 10 times high than determined by yield of benzenecarboxylic acids (BCAs) in burned forest floor (CZIMCZIK et al., 2003). This is because the BCA method is very selective for highly condensed carbon in large clusters. However, the Gustafsson method for C_{pyr} (soot) is less specific.

Table 6: Relative intensities (percent of total area) of the ^{13}C CPMAS (CP) and BDMAS (BD) NMR spectra.

Site	Depth [cm]	Method	Range [ppm]			
			0-47	47-110	110-160	160-205
			Alkyl	O- / di-O-alkyl	Aromatic/phenolic	Carboxyl/carbonyl
R	8-25	CP	13.3	0	86.7	0
H1	0-6	CP	26.7	36.8	18.7	17.8
H2	0-9	CP	18.7	35.7	27.4	18.2
	9-40	CP	27.8	29.5	29.4	13.3
P2	0-5	CP	16.5	40.5	21.9	21.1
		BD	11.4	29.9	26.7	32.0
	5-25	CP	20.9	42.9	15.7	20.4
P3	0-18	CP	30.1	38.6	20.1	11.2
		BD	25.4	28.1	28.2	18.3
G1	0-25	CP	22.4	39.8	21.6	16.2
		BD	17.6	36.7	31.3	14.4
	25-60	CP	26.1	36.2	26.4	11.3
		BD	27.2	27.2	32.0	13.6
G2	0-6	CP	25.7	38.3	17.1	18.9
		BD	26.4	25.5	21.0	27.1
[1]300 Soils	varying	CP	25	45	20	10

[1]MAHIEU et al. (1999)

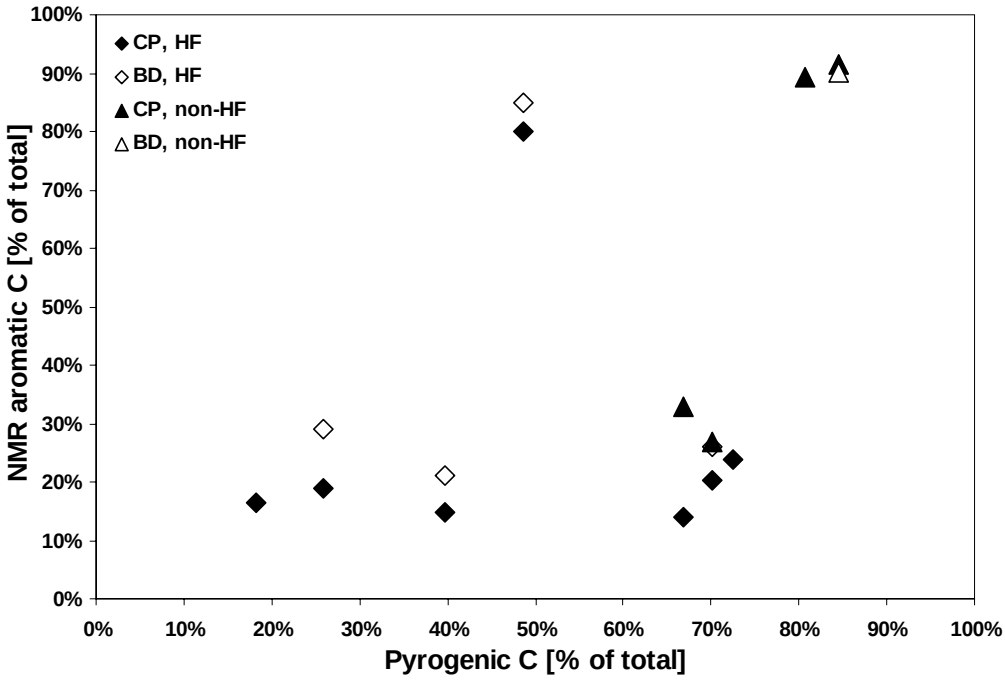

Figure 5: Pyrogenic C *vs.* NMR aromatic C in topsoil samples.

FERNANDES et al. (2003), who compared thermal oxidation and NMR in main precursors of pyrogenic C in urban soils (diesel soot, urban dust), also found no correlation. Especially for diesel soot, an overestimation of C_{pyr} by thermal degradation was indicated. Less severe oxidation procedures, such as the UV photo-oxidation proposed by SKJEMSTAD et al. (1999), are probably more appropriate for determining pyrogenic C.

The overall characterization of organic matter in the soils from Stuttgart indicated that high proportions of combustion-derived C (C_{pyr}) were frequently present. This suggests substantial differences in biochemical behavior against environmentally hazardous compounds and microbial activity (BEYER et al., 2001). However, neither thermal oxidation nor NMR spectroscopy were appropriate for the determination of C_{pyr} proportions. As tradtitional C_{org} analysis does not distinguish between fractions, new analytical approaches are needed.

4.2 Microbial characterization

4.2.1 Microbial biomass

The contents of microbial biomass (CFE) in 0-30 cm ranged between 17 µg C g^{-1} and 1840 µg C g^{-1} and were comparable to urban topsoils studied by MACHULLA (2000). These values were also comparable to arable and grassland soils, but forest soils showed distinctly higher amounts (e.g. MACHULLA, 2000; SOMMER et al., 2002). Stocks of C_{mic} (CFE) were highly variable between the sites and years, ranging from 0.2 to 4.7 t C_{mik} per hectare in the upper 30 cm of the profiles (Fig. 6; Tab. S3-S5). Thus, the maximum stocks of biomass C in topsoils from Stuttgart were higher than for arable, forest, grassland and urban topsoils studied by MACHULLA (2000). When comparing 2000 with 2001 / 2002, the biggest C_{mic} (CFE) stock changes were found at park area 1, where the site for soil sampling had to be shifted in 2001 by 100 m due to construction work. Therefore, the microbial biomass variables from P1 collected in 2000 were considered separately during site comparisons and statistical analysis. On average, significantly lower biomass-C stocks were found in the soil from the railway area, whereas biomass-C stocks were significantly highest at park area 1 and garden area 2 (ANOVA; $p<0.05$; Tab. 8).

Contents of C_{mic} (SIR) ranged from 17 mg C 100 g^{-1} to 488 mg C 100 g^{-1} and were in the range of arable and grassland topsoils (HÖPER, 1999; TSCHERKO et al., 2000). The significantly lowest biomass (SIR) stocks of all sites were found for R and G1, while differences between the other sites were not significant (Tab. 8). Ranking the other sites, however, showed variable shifts, with the biggest changes occurring for the soil at the apartment building. In this soil, the higher stock of C_{mic} (SIR) compared to C_{mic} (CFE) indicated the predominance of microorganisms that readily oxidize glucose. In contrast, the soil microbial community in the top 30 cm of garden area 1 responded only weakly to glucose addition, C_{mic} (SIR) was comparable to C_{mic} (CFE).

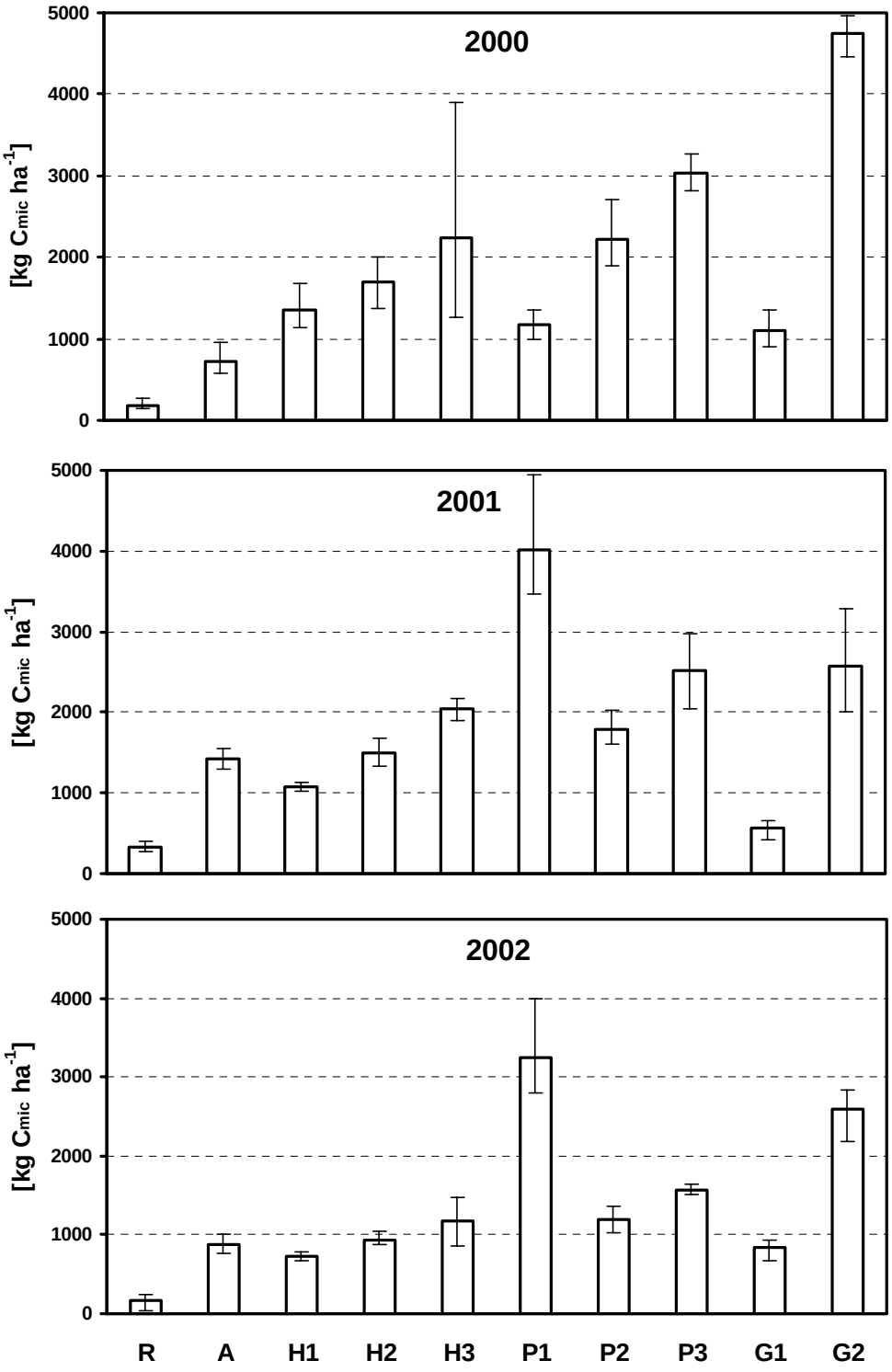

Figure 6: Temporal dynamics of microbial biomass (CFE) calculated for 0-30 cm depth with respect to bulk density and soil skeleton (*N*=3; ±range).

Table 8: Microbial biomass calculated for 0-30 cm depth with respect to bulk density and soil skeleton (3-year means; *N*=9 ; *N*=6 for P1; ±SD).

Site	C_{mic}		N_{mic}
	CFE	SIR	CFE
	[t ha^{-1}]		[kg ha^{-1}]
R	**0.2 ± 0.1**	**0.8 ± 0.3**	**24 ± 16**
A	1.0 ± 0.3	5.3 ± 1.4	193 ± 127
H1	1.1 ± 0.3	3.4 ± 0.6	162 ± 75
H2	1.4 ± 0.4	3.4 ± 1.3	199 ± 36
H3	1.8 ± 0.9	4.6 ± 3.2	281 ± 191
P1	**3.6 ± 0.8**	6.0 ± 2.6	**722 ± 231**
P2	1.7 ± 0.5	3.6 ± 1.9	230 ± 117
P3	2.4 ± 0.7	4.0 ± 1.8	350 ± 60
G1	0.8 ± 0.3	**1.2 ± 0.3**	127 ± 44
G2	**3.3 ± 1.2**	5.9 ± 2.1	**545 ± 177**

bold: significantly different (ANOVA, Student-Newmans-Keuls-test, $p<0.05$)

As in the case of biomass C, the N_{mic} stocks at the railway area were significantly the lowest, while they were highest at P1 and G2 (Tab. 8). The other soils exhibited slight shifts in ranking. Furthermore, microorganisms in the topsoil at the apartment building and park area 1 were relatively enriched in biomass-N compared to C_{mic}. In contrast, soil microorganisms at park area 2 and especially the railway area were relatively depleted in biomass-N.

In summary, the microbial biomass determinations revealed that the upper 30 cm of soil at the railway area was extremely unsuitable for the growth of microorganisms, whereas garden area 2 and park area 1 were most favorable compared to the other sites.

4.2.2 Microbial activity

Dehydrogenase activities in topsoils from Stuttgart encompassed a wide range from 0 to 16902 µg TPF g^{-1} 16 h^{-1}. This range was distinctively higher than in other urban and arable soils (KANDELER et al., 2001; MACHULLA, 2000). Dehydrogenase activities on an area basis were highly variable when comparing sites and years (Fig. 7; Tab. S3-S5). Note, however, that the activities were distinctively lower in the 2002 samples, probably because of the high precipitation. The shift in sampling site P1 is mainly responsible for the temporal dynamics 2000 *vs.* 2001 / 2002. Consequently microbial activity data collected at P1 in 2000 were considered separately. The railway area had extremely low dehydrogenase activities in the top 30 cm, significantly lower than all other sites(Tab. 9).

The maxima and the range for arylsulphatase activities (0 – 663 µg p-nitrophenol g^{-1} h^{-1}) in the studied urban topsoils were much lower than in arable and forest soils (KANDELER et al., 2001; TSCHERKO et al., 2000). Temporal dynamics and differences between the sites were highly variable (Fig. 8). However, arylsulphatase activities were apparently unaffected by the high precipitation in 2002. In 2000 the lowest activities were observed. The railway area was characterized by extremely low activitites in the upper 30 cm, significantly lower compared to P1, G2, H2, P3, P2 and H3 (Tab. 9).

The range and maxima for urease activities were lower compared to arable soils, for N-mineralization higher (TSCHERKO et al., 2000). The sites differed considerably (Tab. 9, S3-S5). The top 30 cm of the railway area exhibited very low urease activitities and N-mineralization rates and extremely low rates of potential NH_4-oxidation. The means in 0-30 cm depth were significantly lower than at all other sites. The highest urease activities were detected at P1 and G2, while for N-mineralization the statistical differences between the other sites were smaller. An extremely high (but not significant) potential NH_4-oxidation was measured in the topsoil at P1. The reasons for this are unclear. The maxima for alkaline phosphatase activities in 0-30 cm were distinctly higher compared to arable and grassland soils (KANDELER et al., 2001). On an area basis, activities were significantly lowest at the railway area and significantly highest at P1 compared to the other sites.

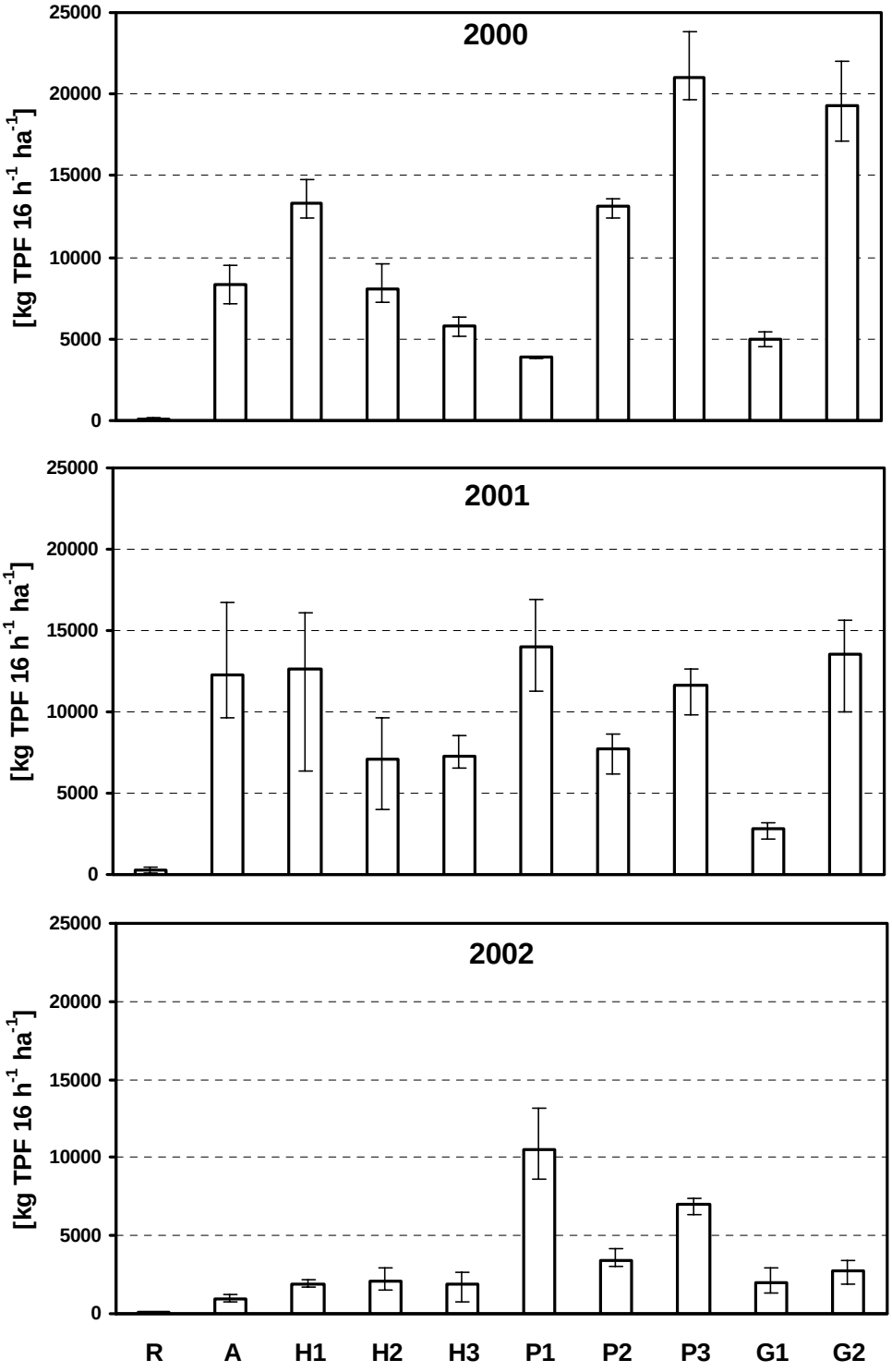

Figure 7: Temporal dynamics of dehydrogenase activity calculated for 0-30 cm depth with respect to bulk density and soil skeleton (*N*=3; ±range).

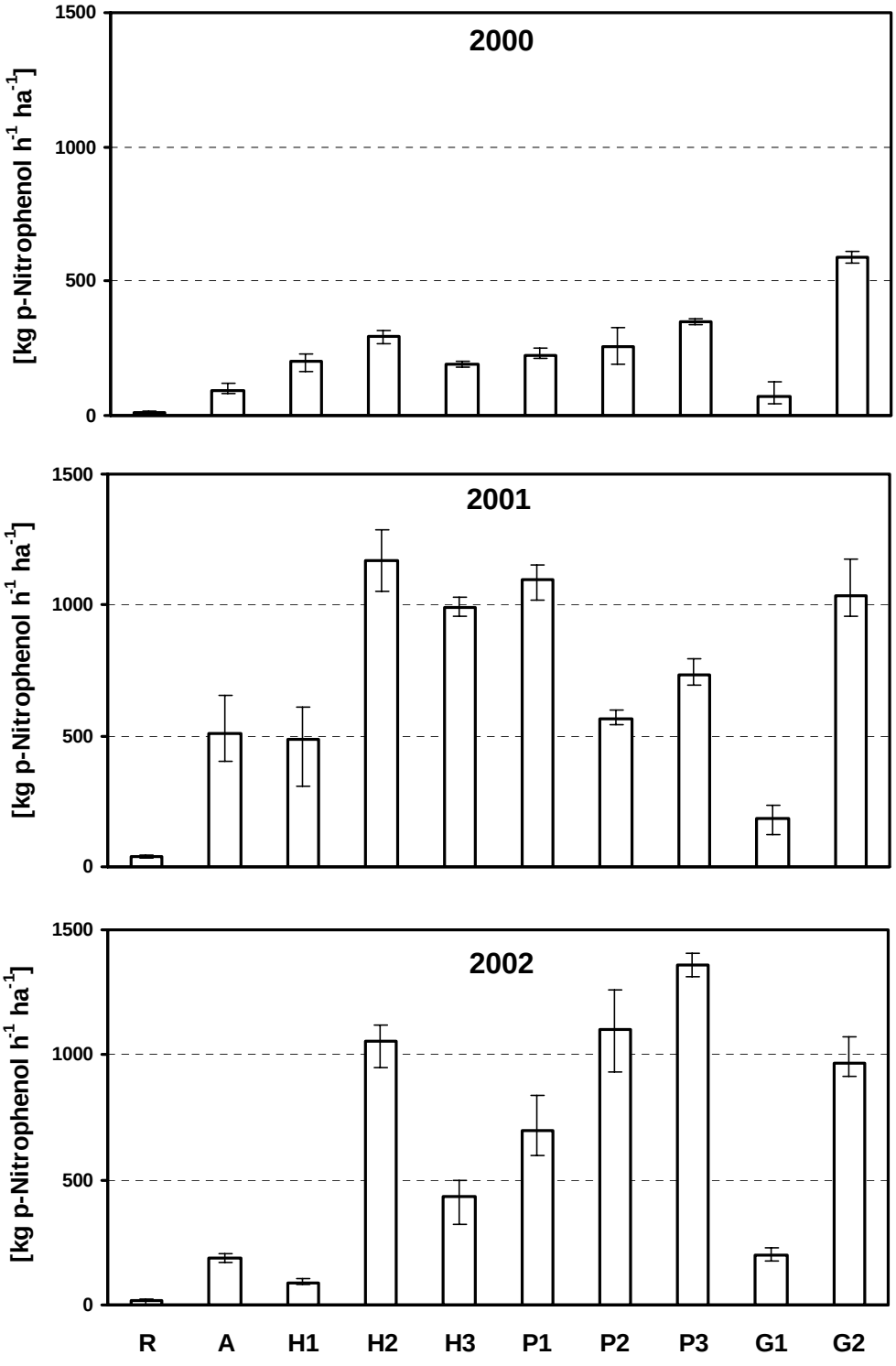

Figure 8: Temporal dynamics of arylsulphatase activity calculated for 0-30 cm depth with respect to bulk density and soil skeleton (*N*=3; ±range).

Table 9: Microbial activity calculated for 0-30 cm depth with respect to bulk density and soil skeleton (3-year means; *N*=9 ; *N*=6 for P1, NH_4-oxidation, N-mineralization, phosphatase; ±SD).

Site	Dehydro-genase	Urease	NH_4-oxidation	N-mineralization	Arylsulphatase	Phosphatase
	[t TPF 16 h^{-1} ha^{-1}]	[kg N 2 h^{-1} ha^{-1}]	[g NO_2-N 6 h^{-1} ha^{-1}]	[kg N 28 d^{-1} ha^{-1}]	[kg p-Nitrophenol h^{-1} ha^{-1}]	[t Phenol 3 h^{-1} ha^{-1}]
R	**0.1 ± 0.1**	**47 ± 19**	**3 ± 2**	**18 ± 11**	**23 ± 15**	**1.3 ± 0.6**
A	7.2 ± 5.4	123 ± 45	162 ± 66	53 ± 24	265 ± 200	7.5 ± 2.7
H1	9.3 ± 6.2	230 ± 128	389 ± 204	85 ± 48	259 ± 195	10.8 ± 3.4
H2	5.8 ± 3.2	156 ± 61	310 ± 203	**111 ± 42**	**839 ± 420**	13.1 ± 1.6
H3	5.0 ± 2.5	204 ± 39	**906 ± 682**	**189 ± 77**	**539 ± 357**	11.8 ± 3.4
P1	12.2 ± 3.0	**522 ± 130**	**3299 ± 3253**	**135 ± 53**	**896 ± 237**	**28.9 ± 6.9**
P2	8.1 ± 4.3	322 ± 61	**1399 ± 1013**	**212 ± 92**	**641 ± 382**	15.1 ± 4.8
P3	13.2 ± 6.4	318 ± 107	**943 ± 593**	133 ± 23	**812 ± 442**	17.9 ± 2.1
G1	3.3 ± 1.5	105 ± 24	467 ± 418	**100 ± 49**	151 ± 72	5.7 ± 1.9
G2	11.8 ± 7.5	**460 ± 220**	**1468 ± 1310**	**181 ± 61**	**865 ± 221**	16.9 ± 3.4

bold: significantly different (ANOVA, Student-Newmans-Keuls-test, $p<0.05$)

Overall, microbial activities in the upper 30 cm of the railway area were extremely low and significantly lower than at the other sites. In contrast, the highest activities were found in the topsoil at park area 1.

4.3 Evaluation of soil microbial habitat quality

4.3.1 Temporal robustness of microbial variables

Soil heterogeneity or seasonal changes of moisture and temperature may influence, but should not bias, the results of a field study. One difficulty in evaluating soil microbial variables is determining how often samples have to be taken until temporal dynamics have no effects on statistical differences between individual sites. We therefore analyzed the robustness of microbial variables where data had been collected over three years (P1 omitted due to shift in sampling site, Tab. 10).

Table 10: Temporal differences between microbial variables at nine individual sites (ANOVA, Student-Newmans-Keuls-test, $p<0.05$)

Microbial variable	Number of sites with		
	no differences between 3 years	differences between 2 years	differences between each year
C_{mic} (CFE)	2	7	0
C_{mic} (SIR)	2	5	2
N_{mic}	3	4	2
Dehydrogenase	1	6	2
Urease	2	6	1
Arylsulphatase	1	3	5

The results indicate that sampling in two different years enhances the robustness of microbial variables, with biomass measurements being less variable than determinations of microbial activity. Arylsulphatase activity showed the highest temporal variation, indicating that this variable is not suitable for evaluating the habitat function of soils for microorganisms (see also Fig. 8).

4.3.2 Aggregation of microbial variables

The new variable **microbial potential** was calculated to aggregate the soil microbial data (SOMMER et al., 2002). The seven microbial variables from the soil sampling in 2000 - C_{mic} (CFE), C_{mic} (SIR), N_{mic}, anaerobic N-mineralization, and activity of dehydrogenase, urease and arylsulphatase - were aggregated in the synthetic variable microbial potential. For the topsoil data from 2001-2002, aerobic instead of anaerobic N-mineralization, and, in addition, NH_4-oxidation and phosphatase activity were included. The value of each variable was normalized for the range from 0 to 1:

$$Normalized\ldots value\ldots of\ \ldots a\ldots Variable = \frac{Value - SampleMinima}{SampleMaxima - SampleMinima}$$

Soil sampling 2000:

Microbial Potential = Arithmetic Mean Normalized Values C_{mic} (CFE), C_{mic} (SIR), N_{mic}, Dehydrogenase, Urease, Anaerobic N-Mineralization, Arylsulphatase

Soil sampling 2001 and 2002:

Microbial Potential = Arithmetic Mean Normalized Values C_{mic} (CFE), C_{mic} (SIR), N_{mic}, Dehydrogenase, Urease, Aerobic N-Mineralization, Arylsulphatase, NH_4-Oxidation, Phosphatase

Microbial biomass and activity were considered equally in calculating the microbial potential (Tab. 11, S6).

Representative frequency distributions of microbial potentials are shown for the 2000 sampling (Fig. 9). Based on the respective logarithmic frequency distribution of microbial potentials and minima in their distributions, five classes were defined for each year (SOMMER et al., 2002; Tab. 11.).

The microbial potential for the soil sampling 2000 ranged from 0.005 to 0.870, for 2001 from 0.011 to 0.819, and for 2002 from 0.025 to 0.631 (Tab. 12). Despite the range of each variable from 0 to 1, no site showed concomitantly high values for each microbial variable.

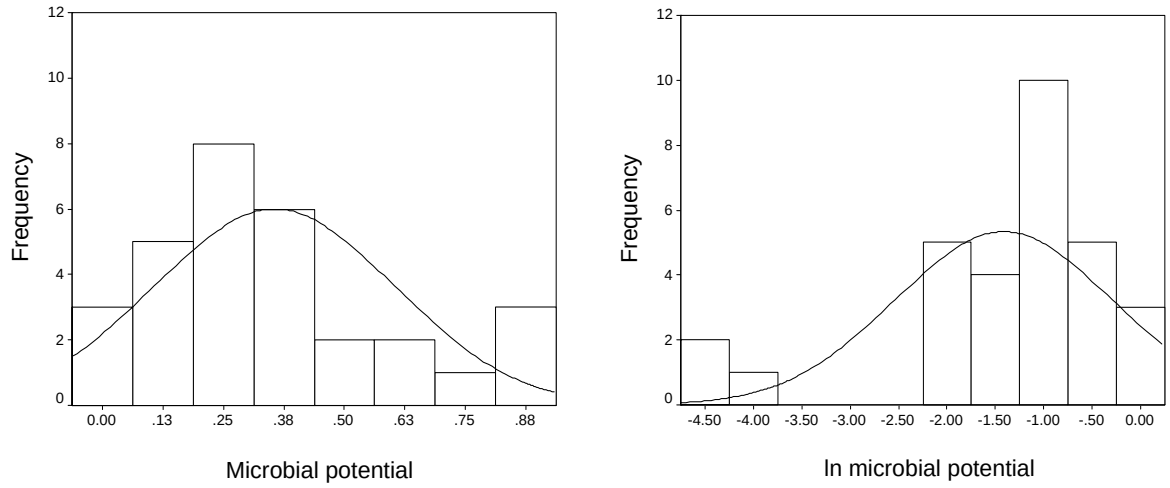

Figure 9: Frequency distribution of microbial potentials and ln(microbial potentials) soil sampling 2000.

Table 11: Classification of urban soils with respect to the habitat function for soil microorganisms based on microbial potentials.

Classification	Soil sampling 2000		Soil sampling 2001		Soil sampling 2002	
	Range	Frequency	Range	Frequency	Range	Frequency
very poor	< 0.05	1	< 0.01	0	< 0.02	0
poor	0.05 - 0.22	2	0.01 - 0.14	2	0.02 - 0.08	1
medium	0.22 - 0.54	5	0.14 - 0.47	4	0.08 - 0.37	6
good	0.54 - 0.78	1	0.47 - 0.78	3	0.37 - 0.61	1
very good	> 0.78	1	> 0.78	1	> 0.61	2

Most sites were classified as medium because extreme values for one variable were balanced by medium values for another variable. The soil at the railway area has the lowest habitat quality for microorganisms, followed by garden area 1. The soil at park area 1 had the highest quality,

followed by garden area 2 and park area 3. Medium habitat quality for microorganisms was indicated for the upper 30 cm at the other sites.

Table 12: Microbial potential and site classification soil sampling 2000, 2001 and 2002 (class limits Tab. 11).

Site	Soil sampling 2000		Soil sampling 2001		Soil sampling 2002	
	Microbial potential	Classification	Microbial potential	Classification	Microbial potential	Classification
R	.005	very poor	.011	poor	.028	poor
A	.267	medium	.337	medium	.352	medium
H1	.325	medium	.299	medium	.279	medium
H2	.347	medium	.324	medium	.274	medium
H3	.316	medium	.513	good	.357	medium
[1]P1	*.126*	*poor*	*.819*	*very good*	*.744*	*very good*
P2	.448	medium	.452	good	.263	medium
P3	.637	good	.422	medium	.444	good
G1	.164	poor	.072	poor	.186	medium
G2	.870	very good	.575	good	.637	very good

[1]Shift in sampling site

4.3.3 Comparison of microbial variables with soil properties

For individual horizons of the soil profiles, more properties were determined in 2000 than for topsoil samples from the following years. In addition, only in 2000 was pyrogenic C separated from C_{org} by thermal oxidation. Furthermore, as of 2001, DIN ISO methods were also used to measure microbial variables. For analysis of correlations between microbial variables and soil properties, the data set was therefore split in three parts. Statistical analyses of the results from 2000 were performed by including abiotic soil properties (Tab. 13, S1). In order to compare microbial variables from topsoil samples collected in 2001 and 2002, individual abiotic

properties - soil moisture, pH($CaCl_2$), C_t, $C_{carbonate}$, C_{pyr}+C_{org}, N_t and (C_{pyr}+C_{org})-to-N_t ratio - were included (Tab. 15, 17, A2).

Maximum data set of abiotic variables: Soil sampling 2000

Table 13: Pearson correlations between microbial variables and abiotic soil properties from the soil sampling 2000 (*N*=30).

	C_{mic} (CFE)	C_{mic} (SIR)	N_{mic}	Dehydro-genase	Urease	anaerobic N-mineralization	Arylsulphatase	Microbial potential
Sand	.121	.302	-.037	.143	.178	.074	.296	.156
Silt	**.599**	**.670**	.398	**.598**	**.562**	**.533**	**.801**	**.506**
Clay	**.666**	**.725**	**.474**	**.657**	**.590**	**.589**	**.832**	**.570**
Soil moisture	.367	.385	**.547**	.425	.223	.444	.181	.394
pCEC	**.807**	**.771**	**.590**	**.825**	**.681**	**.755**	**.910**	**.603**
pH (H_2O)	**-.602**	**-.530**	**-.561**	**-.725**	**-.595**	**-.740**	**-.474**	**-.547**
pH ($CaCl_2$)	-.285	-.116	-.421	-.386	-.452	**-.515**	-.126	-.365
C_t	**.497**	.159	.412	.292	**.628**	.392	.442	**.478**
$C_{carbonate}$	**.500**	.461	.168	**.534**	**.515**	.458	**.635**	.372
C_{pyr}+C_{org}	.325	.009	**.469**	.128	**.466**	.291	.169	.422
C_{pyr}	.200	.016	.350	.004	.328	.142	.112	.333
C_{org}	.384	-.038	**.499**	.206	**.509**	.373	.162	.444
N_t	**.889**	**.676**	**.901**	**.839**	**.868**	**.907**	**.790**	**.824**
(C_{pyr}+C_{org})/N_t	-.445	**-.660**	-.311	**-.644**	-.268	**-.516**	**-.540**	-.297
C_{org}/N_t	**-.530**	**-.776**	-.440	**-.680**	-.381	**-.578**	**-.650**	-.420

bold: significant (two-tailed) (p<0.01)

Microbial biomass and activities were highly positively correlated with N_t stocks and potential cation exchange capacities, but uncorrelated with C_{pyr}+C_{org} stocks and C_{org} stocks (Tab. 13). For soils developed from construction waste or garbage, positive correlations between C_{mic} (CFE) stocks and N_t were reported by MACHULLA et al. (2001). Topsoils in Stuttgart are sufficiently supplied with nitrogen, showing mean or elevated N_t contents, and have predominantly high

potential CEC, at least partially originating from parent materials (HOLLAND, 1996; STAHR et al., 2003). A higher cation exchange capacity probably indicates greater nutrient availability (HOFMAN et al., 2003). As in forest soils N, in urban soils is a determinant of microbial biomass (WARDLE, 1992). Thus, elevated N_t stocks promote growth and activity of microorganisms in the studied urban soils. For forest soils, C_{mic} (CFE) correlated positively with N_t and potential CEC, and basal respiration also correlated with N_t (JÖRGENSEN et al., 1995; SOMMER et al., 2002). For a variety of arable and meadow soils, microbial biomass and activities were highly positively correlated with N_t (HÖPER, 1999; KAISER et al., 1992).

As thermal oxidation failed to separate pyrogenic from organic C, the microbial available C_{org} could not be determined (Chapter 4.1). Consequently, microbial variables and organic matter did not correlate, as has also been reported for a variety of urban soils by MACHULLA et al. (2001) and WERITZ & SCHRÖDER (1990). In contrast, C_{mic} is highly and positively correlated with C_{org} in forest, arable and grassland soils (WARDLE, 1992).

Correlations between biomass C and clay and silt stocks were also positive, but at a lower level of significance compared to N_t and potential CEC. MACHULLA (2000) reported that only urban soils developed from sludge and garbage showed correlations between C_{mic} (CFE) and clay stocks. In the Stuttgart topsoils, an increasing soil clay content therefore had stabilizing effects on microbial biomass. However, this relationship was not evident for a global-scale variety of arable, grassland, forest and desert soils (WARDLE, 1998).

This study also reveals significant negative correlations between C_{mic} (CFE), dehydrogenase activity, anaerobic N-mineralization and pH (H_2O). These correlations may be irrelevant because the pH differences between the sites were low (7.1 – 8.1). MACHULLA (2000), on the other hand, reported a C_{mic} (CFE) decrease only for acidified urban soils, where pH shifted from 4.8 to pH 2.9. When pH values ranged from 6.8 to 7.7, no correlations with microbial biomass stocks were observed.

The ratios C_{org}-to-N_t and (C_{pyr}+C_{org})-to-N_t were negatively correlated with C_{mic} (SIR) and dehydrogenase acitivity, the C_{org}-to-N_t ratio also with arylsufatase activity. In urban soils, very high (C_{pyr}+C_{org})-to-N_t ratios had low C_{mic} (CFE) stocks, indicating that a poor nutritional quality of soil organic matter tended to restrict microbial growth (MACHULLA, 2000).

We used the abiotic soil properties listed in Table 13 to predict the soil microbial properties in the upper 30 cm of the profiles through stepwise multiple regression models. All models and model variables with the exception of sand and C_t stocks were highly significant (p<0.01).

For predicting C_{mic} (CFE), 81 % of the variance could be explained by the following model:

$$\mathbf{C_{mic}\ (CFE)\ [kg\ ha^{-1}] = -1945.777 + 0.00212\ clay + 0.0475\ C_{org} - 0.0012\ sand}$$

For urease activity, 93 % of the variance could be explained by the following model:

$$\mathbf{Urease\ [kg\ N\ 2\ h^{-1}\ ha^{-1}] = -412.785 + 0.221\ N_t + 0.0177\ C_{carbonate} - 56.786\ C_{org}/N_t - 0.0081\ C_t - 0.548\ pCEC + 48.466\ (C_{pyr}+C_{org})/N_t}$$

For arylsulphatase activity, 82 % of the variance could be explained by the following model:

$$\mathbf{Arylsulphatase\ [kg\ p\text{-}Nitrophenol\ h^{-1}\ ha^{-1}] = -167.867 + 0.00458\ C_{org} - 0.00019\ sand + 0.000291\ clay}$$

The results of the Durbin-Watson-test of residues emphasized that the models for predicting C_{mic} (CFE) stocks, arylsulphatase and urease were valid (Tab. 14). However, the regression model for predicting C_{mic} (SIR), N_{mic}, dehydrogenase, anaerobic N-mineralization and microbial potential were of minor quality, with coefficients of determination between 33 and 82 % (not shown).

Beta coefficients reveal the importance of independent abiotic model variables for explaning dependent microbial variables because dimensional differences between variables were eliminated by standardization. When comparing the valid regression models, clay and C_{org} stocks proved to be of main importance for explaining the regression of microbial biomass. Note, however, that the key abiotic variables for explaining variations of microbial biomass (SIR) in agricultural soils were C_{org}, pH, clay and sand content (OBERHOLZER et al., 1999). In arable and grassland soils, C_{mic} (CFE) could be predicted by including clay, pH and hot-water-extractable carbon (EMMERLING & UDELHOVEN, 2002). Furthermore, estimates of C_{mic} (CFE) stocks in forest soils were possible by including N_t-to-(C_{pyr}+C_{org}) ratios, pH and N_t stocks (SOMMER et al., 2002).

Table 14: Parameters of quality for the multiple linear regression models for predicting microbial variables from the soil sampling 2000.

Regression model	R^2	Durbin-Watson-test	Model variable	Beta
C_{mic} (CFE)	.805	1.549	Clay	.895
			C_{org}	.721
			Sand	-.250
Urease	.934	2.164	N_t	2.851
			$C_{carbonate}$	1.936
			C_{org}/N_t	-1.388
			C_t	-1.985
			pCEC	-1.065
			$(C_{pyr}+C_{org})/N_t$	2.294
Arylsulphatase	.820	1.531	C_{org}	.578
			Sand	-.328
			Clay	1.021

Total N stocks and $(C_{pyr}+C_{org})$-to-N_t ratios in urban soils were the most important abiotic variables for explaining the regression of urease activity, whereas clay stocks best explained the regression of arylsulphatase activity. Basal respiration in forest soils could be estimated from regression models including N_t, pH, $C_{pyr}+C_{org}$ and N_t-to-$(C_{pyr}+C_{org})$ ratios (SOMMER et al., 2002).

In the present study, a multitude of abiotic soil properties were available to analyze relationships with biotic properties. Statistical analysis suggests that mainly N_t stocks, pCEC and clay stocks are suitable as indicators for soil microbial habitat function. Elevated values of these variables promoted microbial biomass and activity in urban soils from Stuttgart. Otherwise, for some microbial variables, an elevated $(C_{pyr}+C_{org})$-to-N_t ratio and C_{org}-to-N_t ratio tended to hamper

microbial activity and growth. This suggests that the quality of the food source for microorganisms might also serve as an indicator.

Minimum data set of abiotic variables

Soil sampling 2001

Table 15: Pearson correlations between microbial variables and abiotic soil properties from the soil sampling 2001 (*N*=30).

	C_{mic} (CFE)	C_{mic} (SIR)	N_{mic}	Dehydro-genase	Urease	NH_4-oxidation	aerobic N-mineralization	Aryl-sulphatase	Phos-phatase	Microbial potential
Soil moisture	.101	.024	.140	.367	.226	.423	.444	.265	.304	.032
pH($CaCl_2$)	.284	.336	.273	.289	.286	.387	.127	.388	.270	.299
C_t	.292	.290	.382	.160	**.475**	.217	.388	.013	.288	.381
$C_{carbonate}$	**.536**	**.659**	**.645**	**.610**	**.621**	**.621**	.437	**.535**	**.541**	**.602**
$C_{pyr}+C_{org}$	.102	.029	.104	-.138	.224	.000	.204	-.198	.072	.142
N_t	**.883**	**.751**	**.828**	**.752**	**.926**	**.844**	**.869**	**.777**	**.912**	**.860**
$(C_{pyr}+C_{org})/N_t$	**-.639**	**-.671**	**-.592**	**-.756**	**-.564**	**-.698**	**-.539**	**-.841**	**-.700**	**-.588**

bold: Significant (two-tailed) (p<0.01)

In the 2001 sampling, microbial biomass and activities in the topsoil were highly and positively correlated with N_t and $C_{carbonate}$ stocks, whereas they were highly and negatively correlated with $C_{pyr}+C_{org}$-to-N_t ratios (Tab. 15).

In order to predict microbial properties in the topsoils in 2001 through stepwise multiple regression models, we used the abiotic soil properties listed in Table 15. Highly significant models (p<0.01) were obtained, and N_t was highly significant for every model.

For predicting C_{mic} (CFE), 75 % of the variance could be explained by the following model:

$$\mathbf{C_{mic}\ (CFE)\ [kg\ ha^{-1}] = 1250.441 + 0.447\ N_t - 0.0076\ (C_{pyr}+C_{org}) - 80.026\ soil\ moisture}$$

For C_{mic} (SIR), 74 % of the variance could be explained by the following model:

C_{mic} (SIR) [kg ha^{-1}] = 5.405 + 0.0409 N_t – 0.00094 (C_{pyr}+C_{org}) + 0.00149 $C_{carbonate}$

For NH_4-oxidation, 75 % of the variation could be explained by the following model:

NH_4-oxidation [g N 6 h^{-1} ha^{-1}] = -257.225 +0.0833 N_t

Table 16: Parameters of quality for the multiple linear regression models for predicting microbial variables (sampling 2001).

Regression model	R^2	Durbin-Watson-test	Model variable	Beta
C_{mic} (CFE)	.754	1.429	N_t	1.012
			C_{pyr}+C_{org}	-.351
			Soil moisture	-.256
C_{mic} (SIR)	.600	1.270	N_t	.744
			C_{pyr}+C_{org}	-.351
			$C_{carbonate}$	.284
NH_4-oxidation	.748	1.286	N_t	.870

The results of the Durbin-Watson-test of residues emphasized that the models for predicting C_{mic} (CFE), C_{mic} (SIR) and NH_4-oxidation tended to autocorrelate positively (Tab. 16). As indicated by the high beta coefficients, N_t stocks were of main importance for explaining regression in each model.

However, the Durbin-Watson-test of residues of regression models for predicting urease, aerobic N-mineralization, arylsulphatase, phosphatase and microbial potential were not valid due to positive autocorrelation (not shown). Coefficients of determination for the latter models varied between 41 and 90 %.

Soil sampling 2002

Table 17: Pearson correlations between microbial variables and abiotic soil properties from the soil sampling 2002 (*N*=30).

	C_{mic} (CFE)	C_{mic} (SIR)	N_{mic}	Dehydro-genase	Urease	NH_4-oxidation	aerobic N-mineralization	Aryl-sulphatase	Phos-phatase	Microbial potential
Soil moisture	.397	.053	.373	.415	.321	**.607**	**.578**	.321	.424	.212
pH($CaCl_2$)	.285	.249	.290	.368	.075	.082	.186	.450	.322	.152
C_t	.181	.116	.012	.143	.430	.195	-.125	.049	.095	.215
$C_{carbonate}$	**.513**	**.727**	.458	.390	**.549**	**.614**	.346	.260	**.469**	**.593**
$C_{pyr}+C_{org}$	-.024	-.302	-.193	.010	.215	-.016	-.168	.044	-.082	-.056
N_t	**.779**	.429	**.668**	**.756**	**.771**	**.782**	**.532**	**.803**	**.773**	**.686**
$(C_{pyr}+C_{org})/N_t$	**-.655**	**-.660**	**-.722**	**-.606**	**-.429**	**-.650**	**-.578**	**-.611**	**-.708**	**-.614**

bold: Significant (two-tailed) (p<0.01)

Comparable to 2001, microbial biomass and activities in the topsoil samples from 2002 were highly and positively correlated with N_t and $C_{carbonate}$ stocks, whereas they were highly and negatively correlated with $C_{pyr}+C_{org}$-to-N_t ratios (Tab. 17).

In order to predict soil microbial properties in the topsoil in 2002 through stepwise multiple regression models, we used the abiotic soil properties listed in Table 18. Highly significant models (p<0.01) were obtained, and N_t and pH ($CaCl_2$) were highly significant for every model.

For arylsulphatase activity, 75 % of the variance could be explained by the following model:

$$\textbf{Arylsulphatase [kg p-Nitrophenol } h^{-1}\ ha^{-1}\textbf{]} = -5010.412 + 0.174\ N_t + 708.784\ pH(CaCl_2) - 0.005\ C_{carbonate} - 0.003\ C_t$$

Table 18: Parameters of quality for the multiple linear regression model for predicting arylsulphatase activities (sampling 2002).

Regression model	R^2	Durbin-Watson-test	Model variable	Beta
Arylsulphatase	.747	1.184	N_t	.904
			$pH(CaCl_2)$	.358
			$C_{carbonate}$	-.273
			C_t	-.326

The results of the Durbin-Watson-test of residues emphasized that the model for arylsulphatase tended to autocorrelate positively (Tab. 18). Nitrogen stocks were of main importance for explaining the regression.

The regression models for the other microbial variables are not shown because they show positive autocorrelation. Coefficients of determination for those models varied between 40 and 50 %.

Compared with 2000, in 2001 and 2002 only a minimum set of abiotic properties were determined in the samples. Statistical analysis suggests that N_t stocks and C_{pyr}+C_{org}-to-N_t ratios are the best indicators for microbial biomass and activity in soils from Stuttgart. Thus, soil microbial habitat quality might be primarily evaluated by considering nutrient supply and soil organic matter quality.

In summary, the correlations and the multiple regression models emphasized that, for predicting microbial biomass and activity in soils from Stuttgart, N_t stocks, pCEC, clay stocks and (C_{pyr}+C_{org})-to-N_t ratios should be determined as a minimum data set. These abiotic variables are therefore suitable indicators for soil microbial habitat quality. Nitrogen stocks always showed strong positive correlations with individual microbial variables. This emphasizes that N_t stock is the most powerful variable for evaluating the habitat function of soils from Stuttgart for microorganisms. Determining fewer abiotic variables hampers the statistic validity of the results, as was shown for the 2001 and 2002 sampling.

4.3.4 Ecotoxicological evaluation

Aqua regia extractable (t: total) and NH_4NO_3 extractable (a: available) fractions of heavy metals from the soil profiles served as a basis for evaluating the ecotoxicological effects of heavy metals on soil microbial biomass and activity. No negative correlations (p<0.01, not shown) between microbial variables and heavy metals were calculated for either fraction, suggesting that soil microorganisms were not hampered.

Thus, a more detailed analysis was performed using stepwise linear regression models in order to determine the effects of heavy metal stocks on variations in soil microbial properties in the upper 30 cm of the profiles (Chapter 3.4). All models and model variables with the exception of Zn were highly significant (p<0.01).

For predicting C_{mic} (CFE) (t: aqua regia extractable; a: NH_4NO_3 extractable), 87 % of the variance could be explained by the following model:

$$\mathbf{C_{mic}\ (CFE)\ [kg\ ha^{-1}] = -232 + 885728\ Hg_a - 375105\ Cd_a + 33504\ Ni_a + 64336\ Cr_a + 1496\ Zn_a - 0.946\ Zn_t}$$

For N_{mic}, 75 % of the variance could be explained by the following model:

$$\mathbf{N_{mic}\ [kg\ ha^{-1}] = -21 + 144924\ Hg_a - 64320\ Cd_a + 12467\ Cr_a + 252\ Zn_a}$$

For C_{mic} (SIR), 74 % of the variance could be explained by the following model:

$$\mathbf{C_{mic}\ (SIR)\ [kg\ ha^{-1}] = -127 + 346\ Zn_a + 8380\ Cr_a + 30844\ Hg_a - 11321\ Cd_a}$$

For urease activity, 84 % of the variance could be explained by the following model:

$$\mathbf{Urease\ [kg\ N\ 2\ h^{-1}\ ha^{-1}] = 47 + 141269\ Hg_a - 62033\ Cd_a + 8471\ Ni_a + 13146\ Cr_a - 2\ Ni_t}$$

Table 7: Parameters of quality for multiple linear regression models for predicting heavy metal effects on microbial variables from the soil sampling 2000.

Regression model	R^2	Durbin-Watson-test	Model variable	Beta
C_{mic} (CFE)	.865	2.199	Hg_a	1.499
			Cd_a	-.973
			Ni_a	.362
			Cr_a	.491
			Zn_a	.280
			Zn_t	-.217
N_{mic}	.753	1.766	Hg_a	1.355
			Cd_a	-.922
			Cr_a	.525
			Zn_a	.260
C_{mic} (SIR)	.744	2.181	Zn_a	.890
			Cr_a	.880
			Hg_a	.719
			Cd_a	-.404
Urease	.838	1.659	Hg_a	1.527
			Cd_a	-1.028
			Ni_a	.584
			Cr_a	.640
			Ni_t	-.487

The results of the Durbin-Watson-test of residues emphasized that the models for predicting C_{mic} (CFE and SIR, respectively), N_{mic} and urease were valid (Tab. 7). However, the regression model for predicting dehydrogenase, anaerobic N-mineralization and arylsulphatase were of minor quality, with coefficients of determination between 15 and 97 % (not shown).

Beta coefficients reveal the importance of independent model variables, i.e. heavy metals, for explaining dependent microbial variables because dimensional differences between variables are eliminated by standardization. In comparing the valid regression models, stocks of NH_4NO_3 extractable (available) fractions of Hg, Cd, Cr and Zn proved to be of main importance for explaining the regression. Only in the case of available Cd, however, did negative effects on microbial biomass and activity occur.

These contradictory findings regarding microbial responses to heavy metals may be partially due to variations in metal availability between different soils (KHAN & SCULLION, 2000). Changes in soil organic matter, oxides, clay content and pH can markedly affect the microbial availability of heavy metals in soils (DAR, 1996; YIN et al., 2002). Furthermore, the lack of negative correlations between stocks of individual metals and microbiological variables suggests that combinations of metals may antagonistically or synergistically affect their overall toxicity (ELLIS et al., 2002; MACHULLA, 2000). The heavy metal contents in the profiles were elevated (STAHR et al., 2003). However only very small portions of them were extractable with ammonium nitrate, which indicates bioavailability. One reason is the high heavy metal sorption capacity of the frequent technogenic in Stuttgart, a condition also observed for soils from Rostock (KAHLE & KRETSCHMER, 1999). Even heavy metal contents exceeding threshold values (BBodSchV) had no effect on microbial biomass and activity in urban soils due to high nutrient contents (WERITZ & SCHRÖDER, 1989). Furthermore, a pronounced heavy metal mobilization in soils from Stuttgart can be excluded in the near future because the pH values are high here. To date, a test value for evaluating dangerous effects of heavy metals on soil organisms has only been proposed for Cd (HERRCHEN et al., 2000). That this value (5 mg Cd kg^{-1}) is distinctly higher than the aqua regia extractable Cd contents in the Stuttgart profiles (STAHR et al., 2003). Based on this proposed test value and on our own results, any negative effects of heavy metals on the studied variables of microbial biomass and activity (both are indicative for the soil habitat function for microorganisms) can therefore be excluded in the topsoils of the ten study sites.

4.3.5 Comparison with approaches for evaluating urban soil quality

Estimation of microbial biomass

The determination of soil microbial biomass is time consuming and expensive. Recently, MACHULLA et al. (2001) developed a procedure for estimating C_{mic} in disturbed soils using anthropogenic parent material and the degree of soil development (Tab. 19). Moreover, a classification of C_{mic} for a variety of ecosystems was proposed. The estimates and determinations for the soils from Stuttgart were therefore compared with a classification modified according to the frequency distribution of C_{mic} (CFE) in order to check the accuracy and modify the recommended estimation procedure (Tab. 21).

Table 19: Estimation and classification of microbial biomass C_{mic} stocks (kg ha^{-1} in 0-30 cm) in anthropogenic soils considering parent material and soil development (MACHULLA et al., 2001).

Parent material	Substrates without A_i-horizon	Raw soils with A_i-horizon	Developed soils with A_h-horizon
Sludge, rubbish	400 - 800: *moderate*	800 - 1600: *medium*	1600 - 3200: *high*
Construction waste			
Stone content <30%	200 - 400: *low*	400 - 800: *moderate*	800 - 1600: *medium*
Stone content >30%	< 200: *very low*	200 - 400: *low*	400 - 800: *moderate*
Ash, slag	< 200: *very low*	200 - 400: *low*	400 - 800: *moderate*
Mining deposits	< 200: *very low*	200 - 400: *low*	400 - 800: *moderate*

The microbial biomass in 0-30 cm depth in the Stuttgart soils was classified in five levels based on the frequency distribution of C_{mic} (CFE) values and their logartihmic values (Tab. 20; distribution not shown). Five levels, instead of six proposed by MACHULLA et al. (2001) were regarded as adequate by offices for urban planning and by environmental agencies to evaluate the issues of protecting the climate, water, soil, species and biotopes (RICHTER et al., 2003).

Table 20: Proposed classification of microbial biomass C_{mic} stocks (kg ha^{-1} in 0-30 cm) in urban soils from Stuttgart.

C_{mic} (kg ha^{-1})	Classification
< 360	very low
360 - 870	low
870 - 2040	moderate
2040 - 3630	high
> 3630	very high

Table 21: Comparison estimated with determined C_{mic} stocks (kg ha^{-1} in 0-30 cm) and classification.

Site	Estimation	Classification	Soil sampling 2000	Classification	Mean 2001-2002	Classification
	MACHULLA et al. (2001)					
R	200 - 400	low	180	very low	247	very low
A	800 - 1600	medium	728	low	1155	medium
H1	800 - 1600	medium	1351	medium	910	medium
H2	800 - 1600	medium	1694	medium	1217	medium
H3	800 - 1600	medium	2231	high	1608	medium
[1]P1	*800 - 1600*	*medium*	*1166*	*medium*	*3627*	*high*
P2	800 - 1600	medium	2219	high	1491	medium
P3	1600 - 3200	high	3034	high	2044	high
G1	400 - 800	moderate	1103	medium	703	low
[2]G2	-	-	4743	very high	2580	high

[1]Shift in sampling site

[2]Natural, disturbed substrates omitted

The boundaries for classification were slightly higher than MACHULLA et al. (2001) proposed for various ecosystems. Estimated and determined C_{mic}-stocks were in good agreement (Tab. 21). Furthermore, repeated determinations of biomass in consecutive years improved the predictive power of the C_{mic} estimation procedure.

The soil at garden area 2, developed from tipped natural substrates, could not be classified based on MACHULLA et al. (2001) and the procedure slightly underestimated C_{mic}-stocks at H3 by 13 % with respect to the upper estimation limit. As we observed 0.6- to 1.5-fold differences for C_{mic} between yearly measurements and average values at individual sites, the minor C_{mic} underestimations for the Stuttgart soils are negligible. We therefore can recommend the modified procedure for estimating C_{mic}-stocks in Stuttgart (Tab. 22). Depending on the required accuracy, however, determinations of C_{mic} might also be necessary.

Table 22: Estimation and classification of microbial biomass C_{mic} stocks (kg ha^{-1} in 0-30 cm) in urban soils from Stuttgart considering parent material and soil development.

Parent material	Substrates without A_i-horizon	Raw soils with A_i-horizon	Developed soils with A_h-horizon
Natural substrates	870 - 2040: *medium*	2040 - 3630: *high*	> 3630: *very high*
Sludge, rubbish	360 - 870: *low*	870 - 2040: *medium*	2040 - 3630: *high*
Construction waste			
Stone content <30%	< 360: *very low*	360 - 870: *low*	870 - 2040: *medium*
Stone content >30%	< 360: *very low*	< 360: *very low*	360 - 870: *low*
Ash, slag	< 360: *very low*	< 360: *very low*	< 360: *very low*
Mining deposits	< 360: *very low*	< 360: *very low*	< 360: *very low*

Recommendations for evaluating microbiological quality of soils

An international round table suggested a stepwise procedure for evaluating soil microbial quality (RÖMBKE & KALSCH, 2000). In a first step, biomass (CFE, SIR) and aerobic N-mineralization must be determined using DIN ISO methods. The second, facultative step includes DIN ISO determinations of NH_4-oxidation and dehydrogenase activity. Only in well-founded cases are additional, accepted determinations (e.g. activities of soil enzymes) necessary. According to these recommendations the evaluation of urban soils from Stuttgart was repeated by including only DIN ISO determinations from 2001 and 2002 (Tab. 23).

The results of the evaluation that consider only DIN ISO determinations were comparable to those obtained by well-established, simple laboratory methods (Tab. 21). Soils at the railway area, followed by garden area 1, were of poor habitat quality for microorganisms. The highest habitat quality was at park area 1, followed by garden area 2, while all other soils had a medium quality. If planning procedures require the accurate evaluation of urban soil habitat quality for microorganisms, we can therefore recommend the exclusive use of the above DIN ISO methods.

Table 23: Microbial potentials and classification using DIN ISO determinations for 2001 and 2002 (class limits Tab. 24).

Site	2001		2002	
	Microbial potential	Classification	Microbial potential	Classification
R	.039	very poor	.016	very poor
A	.339	medium	.225	medium
H1	.317	medium	.180	medium
H2	.315	medium	.169	poor
H3	.546	good	.242	medium
P1	.667	very good	.511	very good
P2	.447	good	.206	medium
P3	.402	medium	.276	medium
G1	.093	poor	.144	poor
G2	.583	good	.410	good

Table 24: Classification of uban soils sampled in 2001 and 2002 with respect to habitat function for soil microorganisms based on microbial potential using DIN ISO methods.

Evaluation	2001		2002	
	Range	Frequency	Range	Frequency
very poor	< 0.04	1	< 0.02	1
poor	0.04 - 0.15	1	0.02 - 0.17	2
medium	0.15 - 0.42	4	0.17 - 0.29	5
good	0.42 - 0.61	3	0.29 - 0.47	1
very good	> 0.61	1	> 0.47	1

4.3.6 Integration of the soil microbial habitat function in the overall framework for evaluating soil functions

Natural soil functions are very valuable when evaluating soils, with the habitat function being the pivotal function. Within the higher-ranking subproject "Entwicklung von Bewertungssystemen für Bodenressourcen in Ballungsräumen", the natural soil functions for Stuttgart are assessed as a prerequisite for the overall conservation-related evaluation of the soil (STAHR et al., 2003). The habitat function for microorganisms can be integrated after gross, medium or fine evaluation, depending on the urban planning area and the purpose, e.g. land use plan, development plan, open space plan or environmental risk assessment for the lower planning level scale 1:10,000 and higher (AD-HOC-AG BODEN, 2003; FLAIG et al., 2003).

Natural soil habitat function for microorganisms

Gross evaluation

Microbial biomass in urban soils of Stuttgart and other cities is closely and positively correlated with enzymatic activities (MACHULLA, 2000; WERITZ, 1990). High microbial biomass indicates good living conditions (HÖPER & RUF, 2003). Furthermore, changes in microbial biomass and soil enzyme activities may be manifested over a shorter time scale than changes in chemical properties (EMMERLING et al., 2002). Microbial biomass in Stuttgart topsoils was less variable between the years than microbial activity (Chapter 4.3.1). Thus, C_{mic} is probably a suitable bioindicator if quick and inexpensive investigations are required (BECK, 1986).

Data basis: Soil maps – optional soil survey (KA 4: AG BODEN, 1994)
Assortment of sites according to UMWELTMINISTERIUM BADEN-WÜRTTEMBERG (1995)

Derivation of variables: Gross evaluation of the habitat function for soil microorganisms is performed by estimating and classifying stocks of C_{mic} in 0-30 cm depth by the proposed procedure (Tab. 22).

Variables relevant for the evaluation:

- parent material
- soil development (A_i/A_h horizon)

Evaluation:

Estimates for C_{mic} (kg ha^{-1})	Habitat function for microorganisms
< 360	very poor
360 - 870	poor
870 - 2040	medium
2040 - 3630	good
> 3630	very good

Medium evaluation

For a more specified evaluation, soil microbial activities other than biomass have to be estimated because human activities that affect water, temperature and substrate fluctuations also regulate soil microbial populations and soil enzyme activities (EMMERLING et al., 2002). RÖMBKE & KALSCH (2000) also recommended determining biomass and activity when evaluating soil microbiological quality. Microbial potentials are promising indices to assess this quality because they equally consider biomass and activity (SOMMER et al., 2002; TRASAR-CEPADA et al., 1998). We therefore propose estimating microbial potentials for a medium evaluation. At this level, classifying a site requires calculating those essential abiotic soil properties in the regression model that explain 72 % of the variability of microbial potentials (for 0-30 cm depth and square meter with respect to bulk density and soil skeleton).

Data basis: Soil survey (KA 4) in particular horizonation, stone, clay and N_t content, bulk density, potential cation exchange capacity

Assortment of required sampling sites according to UMWELTMINISTERIUM BADEN-WÜRTTEMBERG (1995)

Derivation of variables: Data from a soil survey for 0-30 cm depth serve as the basis for microbial potential estimates by a multiple linear regression model derived in this study and explaining 72 % of the variation. Classification of microbial potentials and habitat evaluation are accomplished following the derived procedure.

Variables relevant for the evaluation (0-30 cm depth) derived from properties of each horizon:

- stone content (% by weight)
- bulk density (g cm^{-3})
- N_t stock (g m^{-2}): calculated using N_t content considering stone content and bulk density
- clay stock (g m^{-2}): calculated using clay content (% by weight) considering stone content and bulk density
- potential cation exchange capacity stock (g m^{-2}): calculated using pCEC ($cmol_c$ kg^{-1}) considering stone content and bulk density

Algorithm:

Microbial potential = -0.096 + 0.837 N_t stock + 0.00469 clay stock – 5.6 pCEC stock

Evaluation:

Microbial potential based on abiotic soil properties	Habitat function for microorganisms
< 0.05	very poor
0.05 – 0.22	poor
0.22 – 0.54	medium
0.54 – 0.78	good
> 0.78	very good

Fine evaluation

The regression model for estimating the microbial potentials in the Stuttgart soils is of poor quality due to the comparatively small data base (MACHULLA et al., 2001; SOMMER et al., 2002). If a higher accuracy is demanded, e.g. for environmental risk assessment, then biomass and activity have to be determined as a prerequisite for calculating microbial potentials. The DIN ISO methods recommended for C_{mic} (CFE), C_{mic} (SIR), N-mineralization, NH_4-oxidation and dehydrogenase activity are suitable for this purpose (RÖMBKE et al., 2002). Thus, microbial biomass and activity are calculated for 0-30 cm depth and hectare with respect to bulk density and soil skeleton. This calculation also supports the ecological evaluation of sites with respect to their potentials for disintegrating and buffering inorganic and organic pollutants (MACHULLA, 2000).

Data basis: Soil survey (KA 4) in particular horizonation, stone content, bulk density

DIN ISO determinations of C_{mic} (CFE and SIR), N-mineralization, NH_4-oxidation, dehydrogenase activity

Assortment of required sampling sites according to UMWELTMINISTERIUM BADEN-WÜRTTEMBERG (1995)

Derivation of variables: Microbial biomass and activity in individual horizons down to 30 cm depth are determined by DIN ISO methods and calculated with respect to bulk density and soil skeleton. Calculation and classification of microbial potentials and habitat evaluation follow the derived procedure.

Variables relevant for the evaluation (0-30 cm depth) derived from properties of each horizon:

- stone content (% by weight)
- bulk density (g cm^{-3})
- C_{mic} (CFE) (kg ha^{-1}): calculated using C_{mic} (CFE) content (DIN ISO 14240-2) considering stone content and bulk density
- C_{mic} (SIR) (kg ha^{-1}): calculated using C_{mic} (SIR) content (DIN ISO 14240-1) considering stone content and bulk density

- N-mineralization (kg N ha^{-1}): calculated using N-mineralization (DIN ISO 14238) considering stone content and bulk density
- NH_4-oxidation (kg NO_2-N ha^{-1} h^{-1}): calculated using NH_4-oxidation (ISO CD 15685) considering stone content and bulk density
- dehydrogenase activity (kg TPF ha^{-1} 16 h^{-1}): calculated using dehydrogenase activity (DIN 19733-1) considering stone content and bulk density

Algorithm:

$$Normalized\ldots value\ldots of\ \ldots a\ldots MicrobialVariable = \frac{Value - SampleMinima}{SampleMaxima - SampleMinima}$$

Microbial Potential = Arithmetic Mean Normalized Values C_{mic} (CFE), C_{mic} (SIR), N-Mineralization, NH_4-Oxidation, Dehydrogenase activity (biomass and activity equally considered)

Evaluation:

Microbial potential based on biotic soil properties	Habitat function for microorganisms
< 0.05	very poor
0.05 – 0.22	poor
0.22 – 0.54	medium
0.54 – 0.78	good
> 0.78	very good

5 Summary

The conversion of mainly agricultural soils for housing and traffic in Germany is ongoing despite the need to substantially reduce the process against the background of a marginal population growth. In Baden-Württemberg, for example, 11 ha of natural soils are lost per day. Recently, soil functions have become protected by the Federal Soil Protection Act. Natural functions such as the habitat function for soil organisms should therefore be treated with respect in land use planning. Especially in urban soils this function is affected by human activities like sealing, compaction, degradation, landfilling or mixing. In urban soil management, this calls for directing soil use to low quality soils. This, in turn, requires appropriate procedures for evaluating the habitat function for (micro)organisms.

Microorganisms are pivotal in the soil environment because they control transformations and mineralization of natural compounds and xenobiotics. In urban ecosystems, soil chemical and physical properties, including inorganic and organic pollutants, are strongly affected by humans. This alters the growth and activity of soil microorganisms. Furthermore, the composition of the primary microbial food source - soil organic matter – may also be changed by refractory combustion-derived carbon (C_{pyr}) in charcoal and from other sources.

The appropriate indicators for evaluating the habitat quality for microorganims are still under discussion. Beside microbial biomass carbon and soil organic carbon, a variety of methods for measuring biomass and activity have been proposed. Nonetheless, no agreement exists on the set of appropriate microbial variables, even for natural soils.

This study measured microbial biomass and activity in the upper soil horizons at ten sites in Stuttgart in close collaboration with the Institute of Soil Science and the Institute of Landscape and Plant Ecology. Three vegetation periods were covered. Soil microbial methods included measurements of biomass carbon (C_{mic}) with the chloroform-fumigation-extraction (CFE) method and the substrate-induced-respiration (SIR) method, both also by DIN ISO methods. Biomass N (N_{mic}) was also determined by CFE. Soil microbial activity was characterized by measuring dehydrogenase activity, potential NH_4-oxidation and anaerobic and aerobic N-mineralization, additionally using DIN ISO methods. Furthermore, arylsulphatase, urease and alkaline phosphatase activities were determined as potential indicators of heavy metal pollution. Special attention was also given to soil organic matter quality and heavy metal contents. Microbial variables based on an area reference with respect to the coarse fraction and bulk density, together with soil chemical and physical properties, served as a basis for evaluating the habitat function for soil microorganisms.

The soils encompassed a wide range of human disturbance ranging from raw soil at a disused railway area to semi-natural soil near an apartment building, landfilled mixed soils at high-density areas and public parks, to almost undisturbed soils in garden areas. Depending on land use history and especially devastations during Second World War, the contents of heavy metals were elevated.

Combustion-derived carbon was often present in high proportions in topsoils from Stuttgart, suggesting substantial differences in biochemical behaviour towards environmentally hazardous compounds and microbial activity. No detrimental effects of heavy metals on soil microbial biomass and activity were observed, probably due to high contents of clay and soil organic matter as well as high pH values. However, the ecototoxicological evaluation of the soil habitat function for microorganisms remains incomplete because data on organic pollutants were not available.

Soil microbial biomass and activity on an area basis was lowest at the railway area and highest at garden area 2 and park area 1, with the other sites exhibiting intermediate values. A recommendation is made only to measure C_{mic} if time and financial constraints dictate a lower accuracy of the evaluation.

In order to classify and evaluate urban soils from Stuttgart, the variables for biomass and activity were aggregated into the synthetic variable “microbial potential”, which equally considers biomass and activity. Based on the respective frequency distribution, five habitat classes (very poor, poor, medium, good, very good) were distinguished. Accordingly, the soil at the railway area was classified as very poor to poor with respect to the habitat quality for microorganisms. The soil at garden area 2 was classified as good to very good, and the soil at park area 1 was classified as very good. The other sites had mainly medium quality. A well-founded prediction of biomass and activity in Stuttgart topsoils requires a minimum data set including N_t stocks, potential cation exchange capacities (pCEC) on an area basis, clay stocks and $(C_{pyr}+C_{org})$-to-N_t ratios. The different fractions of soil organic matter were unsuitable predictive tools.

Three procedures, differing in accuracy and effort, are proposed for integrating soil microbial habitat function for soils from Stuttgart into the Institute of Soil Science’s overall evaluation framework. First, if a gross evaluation is sufficient, then estimating and classifying microbial biomass based on parent material and soil development is appropriate. Second, a more sophisticated medium evaluation involves calculating microbial potentials with a regression model derived only from abiotic soil data (bulk density; contents of stone, N_t and clay; potential CEC). Third, if a fine evaluation is required, then DIN ISO determinations for C_{mic} (CFE, SIR), N-mineralization, NH_4-oxidation and dehydrogenase activity serve as the basis for calculating microbial potentials under consideration of bulk density and stone content. Finally, the habitat function is evaluated according to the proposed classification of microbial potentials.

Zusammenfassung

In Deutschland schreitet die Umwidmung landwirtschaftlich genutzter Böden für Siedlung und Verkehr unvermindert fort. Vor dem Hintergrund eines stagnierenden Bevölkerungswachstums besteht jedoch die Forderung nach einer deutlichen Reduktion des Bodenverbrauchs. Im Gegensatz dazu gehen jedoch beispielsweise in Baden-Württemberg täglich 11 ha natürlicher Boden verloren. Das neue Bundes-Bodenschutzgesetz schützt jedoch Bodenfunktionen zu denen auch die Lebensraumfunktion für Bodenorganismen gehört. Bei der Landschaftsplanung sollte diese beachtet werden. Insbesondere in Stadtböden wird die Lebensraumfunktion durch Eingriffe des Menschen wie Versiegelung, Verdichtung, Abtrag, Verfüllung oder Durchmischung beeinträchtigt. Deshalb werden Bewertungsverfahren für die Lebensraumfunktion für Boden(mikro)organismen benötigt, um einen schonenden Umgang mit der Ressource Stadtboden zu unterstützen.

Mikroorganismen übernehmen zentrale Funktionen im Boden, da sie die Umwandlung und Mineralisierung natürlicher Verbindungen und der Xenobiotika kontrollieren. In städtischen Ökosystemen werden chemische und physikalische Bodeneigenschaften sehr stark vom Menschen verändert. Dies hat auch Auswirkungen auf Wachstum und Aktivität der Mikroorganismen. Auch deren Nahrungsgrundlage, die organische Bodensubstanz wird durch den Eintrag unvollständig verbrannter Kohlenstoffverbindungen (C_{pyr}) beispielsweise in Form von Ruß und Holzkohle beeinträchtigt.

Mikrobielle Indikatoren für die Bewertung der Lebensraumfunktion sind immer noch in der Diskussion. Neben dem mikrobiell gebundenem Kohlenstoff und dem im Boden gebundenen organischen Kohlenstoff (C_{pyr}+C_{org}), wurde eine Reihe weiterer Parameter vorgeschlagen. Allerdings gibt es bislang auch für natürliche Böden keinen Konsens über die zur Bewertung geeigneten mikrobiellen Parameter.

In dieser Untersuchung wurden deshalb in enger Zusammenarbeit mit dem Institut für Bodenkunde und dem Institut für Landschafts- und Pflanzenökologie, die mikrobielle Biomasse und Aktivität in den oberen Bodenhorizonten an zehn Standorten in Stuttgart über drei Vegetationsperioden untersucht. Der mikrobiell gebundene Kohlenstoff (C_{mic}) wurde mittels der CFE und der SIR Methode bestimmt (teilweise nach DIN ISO), der mikrobiell gebundenem Stickstoff (N_{mic}) mittels der CFE Methode. Die Aktivität wurde durch Messungen der Dehydrogenaseaktivität, potenziellen NH_4-Oxidation sowie der anaeroben bzw. aeroben N-Mineralisation charakterisiert, zusätzlich mit DIN ISO Methoden. Außerdem wurden die Aktivitäten der Arylsulphatase, Urease und alkalischen Phosphatase bestimmt, auch vor dem Hintergrund ihrer möglichen Empfindlichkeit gegenüber Schwermetallen. Besonderer Augenmerk wurde auf die Qualität der organischen Bodensubstanz und die Schwermetallgehalte

gelegt. Mikrobielle Parameter auf Flächenbasis unter Berücksichtigung der Steingehalte und Lagerungsdichten bildeten zusammen mit bodenchemsichen und –physikalischen Eigenschaften die Basis für die Bewertung der Lebensraumfunktion für Bodenmikroorganismen.

Die untersuchten Böden wiesen sehr unterschiedliche Eigenschaften auf. Das Spektrum reichte von Rohboden eines stillgelegten Bahnareals über naturnahen Boden in der Nähe eines Einzelhauses, verfüllte und durchmischte Böden in Blockbebauungen, Parkanlagen und einer Kleingartenanlage bis zu fast ungestörten Boden in einem Hausgarten. In Abhängigkeit von Nutzungsgeschichte und besonders der Folgen des 2. Weltkriegs waren die Schwermetallgehalte erhöht.

Aus Verbrennungsprozessen stammender Kohlenstoff war oft zu hohen Anteilen in Oberböden Stuttgarts vorhanden. Dies deutet auf deutlich abweichendes Verhalten gegenüber Schadstoffen und mikrobieller Aktivität hin. Schwermetalle hatten keinen negativen Einfluß auf mikrobielle Biomasse und Aktivität möglicherweise wegen der hohen Gehalte an Ton und organischer Substanz und hoher pH-Werte. Die ökotoxikologische Bewertung der Lebensraumfunktion für Mikroorganismen ist jedoch unvollständig, da keine Daten über organische Schadstoffe zur Verfügung standen.

Die mikrobielle Biomasse und Aktivität auf Flächenbasis war im Boden des Bahnareals am niedrigsten und im Garten 2 und der Parkanlage 1 am höchsten. Die weiteren Standorte lagen dazwischen. Die Bestimmung von C_{mic} als einzigen Parameter reicht möglicherweise aus die Lebensraumfunktion zu charakterisieren wenn bei der Bewertung keine hohe Genauigkeit aus zeitlichen und finanziellen Gründen verlangt wird.

Zur Klassifizierung und Bewertung der Stadtböden aus Stuttgart wurden die mikrobiellen Variablen in der synthetischen Variablen mikrobielles Potenzial aggregiert wobei Biomasse und Aktivität gleichermaßen Berücksichtigung fanden. Aufgrund der Häufigkeitsverteilung wurden fünf Klassen der Erfüllung der Lebensraumfunktion (sehr gering, gering, mittel, hoch, sehr hoch) ausgeschieden. Der Boden des Bahnareals wies demnach eine sehr geringe bis geringe Erfüllung der Lebensraumfunktion für Mikroorganismen auf wohingegen der Boden des Gartens 2 eine hohe bis sehr hohe und der Boden der Parkanlage 1 eine sehr hohe Funktionserfüllung aufwiesen. Die anderen Standorte wiesen vor allem mittlere Qualitäten auf. Für eine fundierte Abschätzung der mikrobiellen Biomasse und Aktivität in Oberböden der Stadt Stuttgart sollten zumindest die N_t- und Ton-Vorräte, die potenzielle KAK auf Flächenbasis, und die (C_{pyr}+C_{org})-zu-N_t Verhältnisse bestimmt werden. Weder C_{pyr}+C_{org} noch C_{pyr} alleine noch C_{org} alleine wiesen einen Zusammenhang mit mikrobieller Biomasse und Aktivität auf.

Zur Integration der Lebensraumfunktion für Bodenmikroorganismen in das übergeordnete Bewertungsschema des Instituts für Bodenkunde werden drei Vorschläge unterbreitet, die sich in Aufwand und Genauigkeit unterscheiden. Ist eine Grobbewertung der Böden aus Stuttgart

ausreichend, so genügt die Klassifikation und Abschätzung der mikrobiellen Biomasse anhand des Ausgangsmaterials und der Bodenentwicklung. Bei der aufwändigeren Variante werden die mikrobiellen Potenziale allein aus abiotischen Bodendaten (Lagerungsdichte, Gehalte an Steinen, N_t und Ton sowie potenzieller KAK) mittels eines abgeleiteten Regressionsmodells berechnet. Die Bewertung der Lebensraumfunktion erfolgt nach Klasseneinteilung. Das aufwändigste Verfahren hat DIN ISO Bestimmungen für C_{mik} (CFE, SIR), N-Mineralisation, NH_4-Oxidation und der Dehydrogenaseaktivität zur Grundlage. Unter Berücksichtigung der Lagerungsdichten und Steingehalte wird anschließend das mikrobielle Potenzial berechnet, klassifiziert und damit die Lebensraumfunktion für Bodenmikroorganismen charakterisiert.

6 Outlook

Urban soil research in general - and the focus on habitat function - are relatively new approaches, and the database remains very small (GREEN & OLEKSYSZYN, 2002). Even for reference systems based on more than 800 agricultural sites, there is a need to incorporate more data in order to improve models for microbiological soil evaluation (OBERHOLZER & HÖPER, 2000). The soil habitat function is one of the most controversial of the soil functions under discussion (HOCHFELD et al., 2003b). Soil microorganisms are the most abundant group in the soil biocoenosis, but the soil fauna and plant roots also have to be included to evaluate the soil habitat function.

Applied research

The procedures derived in this study for evaluating the habitat quality of topsoils from Stuttgart for microorganisms should be regarded as ideal cases. In order to incorporate these procedures in urban planning, the available digitalized soil data should be used. One promising approach is the use of decomposer communities (earthworms, enchytraeides) as proposed by GRAEFE (1993). This approach is derived from a combination of soil use, water regime, pH and texture, supplemented with soil microbial biomass classified according to parent material and soil development (HÖPER & RUF, 2003). More soil biological studies on the interactions between urban soils and soil organisms would help to improve the quality of the procedures. One strategy might be to conduct DIN ISO lab measurements of at least one variable for biomass (C_{mic} (CFE)) and one for activity (potential NH_4-oxidation) in various urban soils of a distinct planning area encompassing a wide range of human disturbance. Potential NH_4-oxidation is very sensitive to contamination, it is proposed for the assessment of soils and is also used to derive test values according to BBodSchV (HUND-RINKE & LUKOW, 2001) Another advantage is the new field method for potential NH_4-oxidation - involving a reflectometric test kit - proposed by GROMES et al. (2003). For topsoils at park area 1 and 2, the field and lab determinations have already been demonstrated to agree with one another.

The BWPLUS project BWC 20022 “Nachhaltiges Bauflächenmanagement Stuttgart” (LANDESHAUPTSTADT STUTTGART, 2003) focuses on reducting of the utilisation of new inner city areas for industry and housing. We argue for testing whether habitat function might be incorporated into ecological soil policy related to sustainable brownfield development. So far, BWC 20022 considers soil quality only with respect to contaminated sites (KRIEGER, 2003).

Basic research

The ecotoxicological evaluation of the soil habitat remains incomplete because effects of organic pollutants could not be assessed due to missing data. Ideally, the direct comparison of neighbouring urban soils with and without a single pollutant (but otherwise exhibiting equal soil properties) would help identify the microbial indicators of soil pollution. Collaboration with the task force FIGURA would be advantageous (BATEREAU et al., 2003).

Urban soils are often characterized by special depth functions of the soil variables. These have to be taken into account during sampling (SCHLEUSS & MÜLLER, 2001). To date, sampling depths for soil biological studies are restricted to the topsoil (ARBEITSGEMEINSCHAFT ALPEN-ADRIA, 2001). Natural soils, however, are metabolically active and contain substantial numbers of microorganisms down to 4.2 m (TAYLOR et al., 2002). Urban soils frequently contain nutrient-rich garbage in deeper horizons due to landfilling and soil mixing. Nonetheless, current soil evaluation procedures are restricted to 1-2 m soil depth (UMWELTMINISTERIUM BADEN-WÜRTTEMBERG, 1995; HOCHFELD et al., 2003a). An effort should be made to determine whether deeper soil horizons should also be included if a certain level of accuracy is required.

In the proposed evaluation procedures for soils from Stuttgart, the coarse fraction was not regarded as habitat for soil microorganims for practical reasons. CORTI et al. (1998) and AGNELLI et al. (2002), however, have shown that the soil skeleton of natural soils contains substantial amounts of organic carbon, the food source for soil microorganisms. Furthermore, highly altered rock fragments are a favorable environment for the presence and activity of the microbial community (AGNELLI et al., 2001). This raises the question whether the often nutrient-rich coarse fraction of urban soils should be included in the evaluation of the habitat function.

Different human activites that disturb the soil environment are reflected in different adaption times of the microbial community to the new soil conditions. Monitoring biomass and activity as well as soil properties at a given urban site disturbed by defined changes in soil use would be a major step forward in determining whether altered habitat function can be predicted by an evaluation procedure.

In contrast to natural soils, the nutritional quality of soil organic matter for microorganisms in urban soils is unclear, especially with respect to combustion-derived carbon. Incubation experiments with charred plant material mixed with urban soils, combined with measurements of microbial biomass and activity, would help in interpreting the consequences of altered organic matter quality for the microbiological habitat function here.

7 References

AD-HOC-AG BODEN (2003): Methodenkatalog zur Bewertung natürlicher Bodenfunktionen, der Archivfunktion des Bodens, der Gefahr der Entstehung schädlicher Bodenveränderungen sowie der Nutzungsfunktion „Rohstofflagerstätte“ nach BBodSchG. http://www.bgr.de/saf_boden/adhocag/adhocag.html

AG BODEN (1994): Bodenkundliche Kartieranleitung, 4. Aufl., Hannover, 392 S.

AGNELLI, A., S.E. TRUMBORE, G. CORTI, F.C. UGOLINI (2002): The dynamics of organic matter in rock fragments in soil investigated by ^{14}C dating and measurements of ^{13}C. Eur. J. Soil Sci. 53, 147-159.

AGNELLI, A., F.C. UGOLINI, G. CORTI, G PIETRAMELLARA (2001): Microbial biomass-C and basal respiration of fine earth and highly altered rock fragments of two forest soils. Soil Biol. Biochem. 33, 613-620.

AK STADTBÖDEN (1997): Empfehlungen des Arbeitskreises Stadtböden der Deutschen Bodenkundlichen Gesellschaft für die bodenkundliche Kartierung urban, gewerblich, industriell und montan überformter Flächen (Stadtböden), 2. Aufl., Sekretariat büro für bodenbewertung, Kiel, 112 S.

ANDERSON, J.P.E., K.H. DOMSCH (1978): A physiological method for the quantitative measurement of microbial biomass in soil. Soil Biol. Biochem. 10, 215-221.

ARBEITSGEMEINSCHAFT ALPEN-ADRIA (2001): Bodenbiologische Untersuchungs-methoden auf Boden-Dauerbeobachtungsflächen. Empfehlungen einer abgestimmten Vorgehensweise der Unterarbeitsgruppe „Bodenbiologie auf Boden-Dauerbeobachtungsflächen“ der gemeinsamen Arbeitsgruppe „Bodenschutz“ der Arge Alpen-Adria. Hrsg.: Bayerisches Staatsministerium für Landesentwicklung und Umweltfragen. 47 S.

BATEREAU, K., M. MÜLLER, N. KLAAS, B. BARCZEWSKI (2003): Boden- und Flächenressourcenmangement in Ballungsräumen: Innovative Erkundungsmethoden von Schadstoffbelastungen (Vor-Ort-Analytik: Werkzeuge zur Minimierung von Probenahme- und Analytikaufwand) – Schlußbericht BWC 99006. http://bwplus.fzk.de/

BECK, TH. (1986): Aussagekraft und Bedeutung enzymatischer und mikrobiologischer Methoden bei der Charakterisierung des Bodenlebens von landwirtschaftlichen Böden. Veröff. Landwirtsch.-chem. Bundesanstalt Linz/Donau 18, 75-100.

BEYER, L. (1997): Die organische Bodensubstanz anthropogener Böden der Stadt Kiel. Mitteilgn. Dtsch. Bodenkundl. Gesellsch. 84, 123-126.

BEYER, L., P. KAHLE, H. KRETSCHMER, Q. WU (2001): Soil organic matter composition of man-impacted urban sites in North Germany. J. Plant Nutr. Soil Sci. 164, 359-364.

BLOEM, J., T. SCHOUTEN, S. SØRENSEN, A.M. BREURE (2003): Application of microbial indicators in ecological approaches to monitor soil quality. Ambio (in press).

BLUME, H.-P. (1996): Böden städtisch-industrieller Verdichtungsräume. In: Böden als Teile von Landschaften (3.4.4.9), in H.-P. Blume, P. Felix-Henningsen, W.R. Fischer, H.G. Frede, R. Horn and K. Stahr (Hrsg.): Handbuch der Bodenkunde. Ecomed-Verlag Landsberg, 48 S.

BUNDESMINISTERIUM FÜR UMWELT, NATURSCHUTZ UND REAKTORSICHERHEIT (1999): Bundes-Bodenschutz- und Altlastenverordnung (BBodSchV) vom 12. Juli 1999. Bundesgesetzblatt I, Nr. 36.

BURGHARDT, W. (1994): Soils in urban and industrial environments. Z. Pflanzenernähr. Bodenk. 157, 205-214.

CARTER, M.R., E.G. GREGORICH, D.W. ANDERSON, J.W. DORAN, H.H. JANZEN, F.J. PIERCE (1997): Concepts of soil, quality and their significance. In: Gregorich, E.G., Carter, M.R. (Eds.): Soil Quality for Crop Production and Ecosystem Health. Elsevier, Amsterdam, pp. 1-19.

CORTI, G., F.C. UGOLINI, A. AGNELLI (1998): Classing the soil skeleton (greater than two millimeters): proposed approach and procedure. Soil Sci. Soc. Am. J. 62, 1620-1629.

CZIMCZIK, C., C.M. PRESTON, M.W.I. SCHMIDT, E.-D. SCHULZE (2003): How surface fires in Siberian Scots pine forests affects soil organic carbon in forest floor: Stocks, molecular structure, and conversion to black carbon (charcoal). Global Biochem. Cycles 17, 20-1 to 20-14.

CZIMCZIK, C., C.M. PRESTON, M.W.I. SCHMIDT, R.A. WERNER, E.-D. SCHULZE (2002): Effects of charring on mass, organic carbon, and stable carbon isotope composition of wood. Org. Geochem. 33, 1207-1223.

DAR, G.H. (1996): Effects of cadmium and sewage sludge on soil microbial biomass and activity. Bioresour. Technol. 56, 141-145.

DE KIMPE, C.R., J.-L. MOREL (2000) : Urban soil management : a growing concern. Soil Sci. 165, 31-40.

DEUTSCHER BUNDESTAG (1998): Gesetz zum Schutz vor schädlichen Bodenveränderungen und zur Sanierung von Altlasten (Bundes-Bodenschutzgesetz - BBodSchG). Bundesgesetzblatt I, S. 502.

DORAN, J.W., T.B. PARKIN (1996): Quantitative indicators of soil quality: a minimum data set. In: Doran, J.W., Jones, A.J. (Eds.), Methods for assessing soil quality. Soil Science Society of America, Special Publications No. 49, 25-37.

ELLIS, R.J., J.G. BEST, J.C. FRY, P. MORGAN, B. NEISH, M.W. TRETT, A.J. WEIGHTMAN (2002): Similarity of microbial and meiofaunal community analyses for mapping ecological effects of heavy-metal contamination in soil. FEMS Microbiol. Ecol 1344, 1-10.

EMMERLING, C., M. SCHLOTER, A. HARTMANN, E. KANDELER (2002): Functional diversity of soil organisms – a review of recent research activities in Germany. J. Plant Nutr. Soil Sci. 165, 408-420.

EMMERLING, C., T. UDELHOVEN (2002): Discriminating factors of spatial variability of soil quality parameters at landscape-scale. J. Plant Nutr. Soil Sci. 165, 706-712.

FERNANDES, M.B., J.O. SKJEMSTAD, B.B. JOHNSON, J.D. WELLS, P. BROOKS (2003): Characterization of carbonaceous combustion residues. I. Morphological, elemental and spectrocopic features. Chemosphere 51, 785-795.

FLAIG, H., M. STEIERWALD, P. SPATZ, G. GLOMB (2003): Endbericht zum Forschungsvorhaben Bewertung von Forschungsvorhaben im Rahmen des BWPLUS-Schwerpunktthemas „Boden- und Flächenressourcenmanagement in Ballungsräumen“, Teile A und B. unveröffentlicht.

GRAEFE, U. (1993): Die Gliederung von Zersetzergesellschaften für die standortökologische Ansprache. Mittl. Deutsche Bodenkundl. Gesell. 69, 95-98.

GREEN, D. M., M. OLEKSYSZYN (2002): Enzyme activites and carbon dioxide flux in a Sonoran desert urban ecosystem. Soil Sci. Soc. Am. J. 66, 2002-2008.

GROMES, R., S. BEHRENS, E. NAGEL (2003): The use of reflectometric test kits for estimating nitrification and soil invertase activity in the field. J. Plant Nutr. Soil Sci. 166, 179-183.

GRUNICKE, U., R. BÖCKER, M. RICHTER (2002): Ökologische Bewertung von Freiflächen im Ballungsraum Mittlerer Neckar. Beiheft 15. Berichte des Instituts für Landschafts- und Pflanzenökologie der Universität Hohenheim, 58 S.

GUSTAFSSON, Ö., F. HAGHSETA, C. CHAN, J. MCFARLANE, P.M. GSCHWEND (1997): Quantification of the dilute sedimentary soot phase: implications for PAH speciation and bio-availability. Environ. Sci. Technol. 31, 203–209.

HERRCHEN, M., W. KRATZ, A. MARSCHNER, U. NECKER, S. PIEPER, J. RÖMBKE, F. RIEPERT, F. RÜCK, K. TERYTZE, C. THROL, B.-M. WILKE (2000): Eckpunkte zur Gefahrenbeurteilung des Wirkungspfades Bodenverunreinigungen-Bodenorganismen. Fachausschuss „Biologische Bewertung von Böden“ der Fachgruppe 4 „Bodenfunktionen und –belastungen des Bundesverbandes Boden (BVB). (no more available from server).

HINRICHS, H. (2001): Mikrobielle Aktivität und Biomasse in Stuttgarter Stadtböden. Diplomarbeit (unveröffenlicht), Fachhochschule Osnabrück, Fachbereich Agrarwissenschaften, Studiengang Bodenwissenschaften, 115 S.

HOCHFELD, B. (2000): Machbarkeitsstudie zur Ableitung von Kennwerten für nicht unmittelbar ökotoxikologisch wirksame Stoffe und für nicht-stoffliche Einwirkungen auf die natürlichen Bodenfunktionen. http://www.bodenbewertung.de

HOCHFELD, B., A. GRÖNGRÖFT, G. MIEHLICH (2003a): Großmaßstäbige Bodenfunktionsbewertung für Hamburger Böden – Verfahrensbeschreibung und Begründung. Institut für Bodenkunde, Universität Hamburg. http://fhh.hamburg.de/stadt/Aktuell/behoerden/umwelt-gesundheit/umwelt/boden/bodenschutz/fragen/bfb-hamburg.html

HOCHFELD, B., A. GRÖNGRÖFT, G. MIEHLICH (2003b): Neufassung des Hamburger Verfahrens zur Bodenfunktionsbewertung. Tagungsband 3. Marktredwitzer Bodenschutztage, 13. – 15. Oktober 2003, Marktredwitz, Bayern.

HÖPER, H. (1999): Die Bedeutung abiotischer Bodeneigenschaften für bodenmikrobiologische Kennwerte. – Ergebnisse aus der Bodenbauerbeobachtung in Niedersachsen. Mitteilgn. Dtsch. Bodenkundl. Gesellsch. 89, 253-256.

HÖPER, H., A. RUF (2003): Methode zur flächenhaften Darstellung des Bodens in seiner Funktion als Lebensraum von Bodenorganismen für Planungen im mittleren Maßstab. Bodenschutz 2, 41-47.

HOFMAN, J., J. BEZCHLEBOVÁ, L. DUŠEK, L. DOLEŽAL, I. HOLOUBEK, P. ANDĚL, A. ANSORGOVÁ, S. MALÝ (2003): Novel approach to monitoring of the soil biological quality. Environ. Int. 28, 771-778.

HOLLAND, K. (1996): Stadtböden im Keuperland am Beispiel Stuttgarts. Institut für Bodenkunde und Standortslehre, Universität Hohenheim. Hohenheimer Bodenkundl. Heft 39, 228 S.

HOLZWARTH, F., H. RADTKE, B. HILGER (1998): Bundes-Bodenschutzgesetz – Handkommentar. Erich Schmidt Verlag, Berlin.

HUND-RINKE, K., T. LUKOW (2001): Wirkung von Genprodukten auf die Lebensraumfunktion von Böden. UBA-FB 20073250, 72 S.

JÖRGENSEN, R.G., T.-H. ANDERSON, V. WOLTERS (1995): Carbon and nitrogen relationships in the microbial biomass of soils in beech (*Fagus sylvatica* L.) forests. Biol. Fertil. Soils 19, 141-147.

KAHLE, P., H. KRETSCHMER (1999): Zur Inventur von Schwermetallen in Böden des Stadtgebietes von Rostock unter Berücksichtigung von technogenen Substraten und Adsorptionskapazität. Bodenschutz 4, 142-146.

KAISER, E.-A., T. MUELLER, R.G. JOERGENSEN, H. INSAM, O. HEINEMEYER (1992): Evaluation of methods to estimate soil microbial biomass and the relationship with soil texture and organic matter. Soil Biol. Biochem. 24, 675-683.

KANDELER, E. (1993a): Kolorimetrische Bestimmung der Urease-Aktivität. S. 186-189. In: Schinner, F., R. Öhlinger, E. Kandeler, R. Margesin: Bodenbiologische Arbeitsmethoden. Springer Verlag, Berlin, Heidelberg, New York, 389 S.

KANDELER, E. (1993b): Bestimmung der N-Mineralisation im anaeroben Brutversuch. S. 160-161. In: Schinner, F., R. Öhlinger, E. Kandeler, R. Margesin: Bodenbiologische Arbeitsmethoden. Springer Verlag, Berlin, Heidelberg, New York, 389 S.

KANDELER, E., H. GERBER (1988): Short-term assay of soil urease activity using colorimetric determination of ammonium. Biol. Fert. Soils 6, 68-72.

KANDELER, E., C. KAMPICHLER, O. HORAK (1996): Influence of heavy metals on the functional diversity of soil microbial communities. Biol. Fertil. Soils 23, 299-306.

KANDELER, E., D. TSCHERKO, M. STEMMER. S. SCHWARZ, M.H. GERZABEK (2001): Organic matter and soil microorganisms – Investigations from the micro- to the macro-scale. Die Bodenkultur 52, 117-131.

KHAN, M., J. SCULLION (2000): Effect of soil on microbial responses to metal contamination. Environ. Pollut. 110, 115-125.

KÖRDEL, W., J. RÖMBKE (2001): Requirements on physical, chemical and biological testing methods for estimating the quality of soils and substrates. J. Soils & Sediments 1, 98-104.

KRIEGER, N. (2003): Nachhaltiges Bauflächenmanagement Stuttgart. Zwischenbericht anlässlich des Statusseminars des BW-PLUS am 11. und 12.3.2003 im Forschungszentrum Karlsruhe, http://bwplus.fzk.de

LANDESHAUPTSTADT STUTTGART (Hrsg.) (2003): Nachhaltiges Bauflächenmanagement Stuttgart (NBS). – Schlußbericht Kurzfassung. Beiträge zur Stadtentwicklung 34. http://www.isl-projekte.uni-karlsruhe.de/nbs/nbs_kurz.pdf

LANDESANSTALT FÜR UMWELTSCHUTZ (2003): Umweltdaten 2003. http://www.lfu.baden-wuerttemberg.de/lfu/abt2/umweltdaten2003/

MACHULLA, G. (2000): Mikrobielle Aktivität von Böden aus anthropogenen und natürlichen Substraten. Hallenser Bodenwissenschaftliche Abhandlungen 1, 208 S.

MACHULLA, G., H.-P. BLUME, R. JAHN (2001): Schätzung der mikrobiellen Biomasse von Böden aus anthropogenen und natürlichen Substraten – ein Beitrag zu Standortbewertung. J. Plant Nutr. Soil Sci. 164, 547-554.

MAHIEU, N., D.S. POWLSON, E.W. RANDALL (1999) : Statistical analysis of published carbon-13 CPMAS NMR spectra of soil organic matter. Soil Sci. Soc. Am. J. 63, 307-319.

MAURER, T. (2001): Stadtböden aus anthropogenen und natürlichen Substraten in Stuttgart-Ost am Beispiel der Auffüllung „Gaisburger Bach“. Diplomarbeit (unveröffentlicht), Institut für Geologie und Paläontologie, Universität Stuttgart, 92 S.

MEUSER, H. (1996): Technogene Substrate als Ausgangsgestein der Böden urban-industrieller Verdichtungsräume. Schriftenr. Inst. Pflanzenernähr. Bodenkd., Universität Kiel, 35, 221 S.

MINISTERIUM FÜR UMWELT UND VERKEHR BADEN-WÜRTTEMBERG (Hrsg.) (1999): Bodenzustandsbericht Großraum Stuttgart – Schadstoffgehalte der Böden. 107 S.

NACHBARSCHAFSTVERBAND STUTTGART (1992): Klimaatlas. – Klimauntersuchung für den Nachbarschaftsverband Stuttgart und angrenzende Teile der Region, bearb. v. J. Baumüller. Karten mit Erläuterungen.

NANNIPIERI, P. (1994): The potential use of enzymes as indicators of productivity, sustainability and pollution. In: Pankhurst, C.E., Doube, B.M., Gupta, V.V.S.R., Grace, P.R. (eds.): Soil biota: management in sustainable farming systems. CSIRO, East Melbourne, pp. 238-244.

OBERHOLZER, H.-R., H. HÖPER (2000): Reference systems for the microbiological evaluation of soils. VDLUFA-Schriftenreihe 55, Teil 2, Kongressband 2000, 19-34.

OBERHOLZER, H.-R., J. REK, P. WEISSKOPF, U. WALTHER (1999): Evaluation of soil quality by means of microbial parameters related to the characteristics of individual arable sites. Agribiol. Res. 52, 113-125.

ÖHLINGER, R. (1993a): Bestimmung der Dehydrogenase-Aktivität mit TTC. S. 249-252. In: Schinner, F., R. Öhlinger, E. Kandeler, R. Margesin: Bodenbiologische Arbeitsmethoden. Springer Verlag, Berlin, Heidelberg, New York, 389 S.

ÖHLINGER, R. (1993b): Bestimmung der Phosphomonoesterase-Aktivität bei saurem, neutralem und alkalischem pH-Wert. S. 197-200. In: Schinner, F., R. Öhlinger, E. Kandeler, R. Margesin: Bodenbiologische Arbeitsmethoden. Springer Verlag, Berlin, Heidelberg, New York, 389 S.

PLANUNGSGRUPPE ÖKOLOGIE + UMWELT GmbH (2003): Zusammenfassung und Strukturierung von relevanten Methoden und Verfahren zur Klassifikation und Bewertung von Bodenfunktionen für Planungs- und Zulassungsverfahren mit dem Ziel der Vergleichbarkeit. http://fhh.hamburg.de/stadt/Aktuell/behoerden/umwelt-gesundheit/umwelt/boden/bodenschutz

RICHTER, M., U. GRUNICKE, R. BÖCKER (2003): Boden- und Flächenressourcen-Management in Ballungsräumen: Entwicklung von Bewertungsrahmen zur Beurteilung der

ökosystemaren Potenziale verschiedener Nutzungs- und Strukturtypen im urbanen Bereich. – BWPLUS-Forschungsberichte, BWC 99007, Karlsruhe.

RÖMBKE, J., L. BECK, B. FÖRSTER, H.-C. FRÜND, F. HORAK, A. RUF, C. ROSCICZWESKI, M. SCHEURIG, S. WOAS (1997): Boden als Lebensraum für Bodenorganismen bodenbiologische Standortklassifikation – Literaturstudie. In: Handbuch Boden – Texte und Berichte zum Bodenschutz 04/97. Landesanstalt für Umweltschutz Baden-Württemberg, 437 S.

RÖMBKE, J., W. KALSCH (2000): Protokoll des Internationalen Fachgesprächs über „Ansätze für biologische Bewertungsstrategien und –konzepte im Bodenschutz“ – Abschlussbericht. Projektnummer B99014, BMU, 63 S.

RÖMBKE, J., G. LABES, J. WOIWODE (2002): Ansätze für Strategien zur Bewertung des Bodens als Lebensraum für Bodenorganismen. Bodenschutz 2, 62-69.

SCHINNER, F., R. ÖHLINGER, E. KANDELER, R. MARGESIN (Hrsg.) (1993): Boden-biologische Arbeitsmethoden. Springer Verlag, Berlin, Heidelberg, New York, 389 S.

SCHLEUSS, U., F. MÜLLER (2001): Requirements for soil sampling in the context of ecosystem research. Sci. Total Environ. 264, 193-197.

SCHLEUSS, U., Q. WU, H.-P. BLUME (1998): Variability of soils in urban and periurban areas in Northern Germany. Catena 33, 255-270.

SCHLOTER, M., H.-J. BACH, S. METZ, U. SEHY, J.C. MUNCH (2003a): Influence of precision farming on the microbial community structure and functions in nitrogen turnover. Agric. Ecosyst. Environ. 98, 295-304.

SCHLOTER, M., O. DILLY, J.C. MUNCH (2003b): Indicators for evaluating soil quality. Agric. Ecosyst. Environ. 98, 255-262.

SCHMIDT, M.W.I., H. KNICKER, P. HATCHER, I. KÖGEL-KNABNER (1997): Improvement of ^{13}C and ^{15}N CPMAS NMR spectra of bulk soils, particle size fractions and organic material by treatment with 10 % hydrofluoric acid. Eur. J. Soil Sci. 48, 319-328.

SCHMIDT, M.W.I., A.G. NOACK (2000): Black carbon in soils and sediments: Analysis, distribution, implications, and current challenges. Global Biochem. Cycles 14, 777-793.

SKJEMSTAD, J.O., J.A. TAYLOR, R.J. SMERNIK (1999) : Estimation of charcoal (char) in soils. Commun. Soil Sci. Plant Anal. 30, 2283-2298.

SOMMER, M., O. EHRMANN, J.K. FRIEDEL, K. MARTIN, T. VOLLMER, G. TURIAN (2002): Böden als Lebensraum für Organismen – Regenwümer, Gehäuselandschnecken und Bodenmikroorganismen in Wäldern Baden-Württembergs. Hohenheimer Bodenkundl. Hefte 63, 163 S.

STAHR, K., D. STASCH, O. BECK (2003): Entwicklung von Bewertungssystemen für Bodenressourcen in Ballungsräumen. – BWPLUS-Forschungsberichte, BWC 99001, Karlsruhe.

STROBL, W., M. TRAUNMÜLLER (1993): Bestimmung der Arylsulfatase-Aktivität. S. 218–220. In: Schinner, F., R. Öhlinger, E. Kandeler, R. Margesin: Bodenbiologische Arbeitsmethoden. Springer Verlag, Berlin, Heidelberg, New York, 389 S.

TAYLOR, J.P., B. WILSON, M.S. MILLS, R.G. BURNS (2002): Comparison of microbial numbers and enzymatic activities in surface and subsoils using various techniques. Soil Biol. Biochem. 34, 387-401.

TRASAR-CEPADA, C., C. LEIRÓS, F. GIL-SOTRES, S. SEOANE (1998): Towards a biochemical quality index for soils: an expression relating several biological and biochemical properties. Biol. Fert. Soils 26, 100-106.

TSCHERKO, D., E. KANDELER, A. BÁRDOSSY (2000): Klassifikation von bodenmikrobiologischen Eigenschaften. VDLUFA-Schriftenreihe 55, Teil 2, Kongressband 2000, 84-91.

UMWELTBUNDESAMT (2002): Umweltbarometer Boden. http://www.umweltbundesamt.de/dux/bo-inf.htm

UMWELTMINISTERIUM BADEN-WÜRTTEMBERG (Hrsg.) (1993): Dritte Verwaltungsvorschrift des Umweltministeriums zum Bodenschutzgesetz über die Ermittlung und Einstufung von Gehalten anorganischer Schadstoffe im Boden. – Gemeinsames Amtsblatt des Landes Baden-Württemberg, Heft 30, 1029-1036.

UMWELTMINISTERIUM BADEN-WÜRTTEMBERG (1995): Bewertung von Böden nach ihrer Leistungsfähigkeit – Leitfaden für Planungen und Gestattungsverfahren. – Reihe „Luft Boden Abfall“, Heft 31, 54 S.

VANCE, E.D., P.C. BROOKES, D.S. JENKINSON (1987): An extraction method for measuring soil microbial biomass C. Soil Biol. Biochem. 19, 703-707.

WARDLE, D.A. (1992): A comparative assessment of factors which influence microbial biomass carbon and nitrogen levels in soils. Biol. Rev. 67, 321-358.

WARDLE, D.A. (1998): Controls of temporal variability of the soil microbial biomass: a global-scale synthesis. Soil Biol. Biochem. 30, 1627-1637.

WERITZ, N. (1990): Mikrobielle Untersuchungen in Stadtböden unterschiedlicher Nutzung und Schwermetallbelastung zur Charakterisierung der Bodenfunktionalität. Dissertation, Universität Trier.

WERITZ, N., D. SCHRÖDER (1989): Mikrobielle Aktivität in Stadtböden und ihre Bewertung unter besonderer Berücksichtigung von Schwermetallbelastungen. Mitteilgn. Dtsch. Bodenkundl. Gesellsch. 59, 1015-1020.

WERITZ, N., D. SCHRÖDER (1990): Die Bewertung mikrobieller Aktivitäten in Stadtböden als Beitrag zum städtischen Bodenschutz. Mitteilgn. Dtsch. Bodenkundl. Gesellsch. 61, 149-152.

WU, Q.L., L. BEYER, H.-P. BLUME (1995): Charakterisierung der org. Bodensubstanz ausgewählter Böden technogener Substrate. Mitteilgn. Dtsch. Bodenkundl. Gesellsch. 76, 495-498.

YIN, Y., C.A. IMPELLITTERI, S.-J. YOU, H.E. ALLEN (2002): The importance of organic matter distribution and extract soil:solution ratio on the desorption of heavy metals from soils. Sci. Total Environ. 287, 107-119.

8 Supplement

Table S1: Abiotic soil properties: soil sampling 2000 (see also Table 4).

Site	Depth	Soil moisture	C_t	$C_{carbonate}$	$C_{pyr}+C_{org}$	C_{pyr}	C_{org}	N_t	$(C_{pyr}+C_{org})/N_t$	C_{org}/N_t
	(cm)	(%)	----------(kg m^{-2})----------							
R	0-8	11.8	0.8	0.06	0.7	0.3	0.5	0.03	27.7	17.4
	8-25	14.5	7.5	0.57	6.9	3.4	3.6	0.15	47.7	24.5
A	0-10	35.3	3.3	0.68	2.6	0.7	1.9	0.20	13.0	9.3
	10-65	32.8	5.9	4.45	1.5	0.6	0.9	0.66	2.2	1.3
H1	0-6	19.0	2.8	1.00	1.8	0.3	1.5	0.13	14.0	11.5
	6-20	14.8	6.3	2.68	3.6	0.8	2.8	0.24	14.9	11.5
H2	0-9	36.2	7.1	0.78	6.3	4.6	1.7	0.28	22.3	6.1
	9-40	27.9	7.1	0.64	6.5	2.9	3.6	0.68	9.5	5.3
H3	0-6	28.4	3.1	0.53	2.6	0.3	2.3	0.24	10.5	9.5
	6-25	21.6	5.3	1.48	3.8	1.2	2.7	0.38	10.1	7.1
P1	0-8	14.0	3.8	2.36	1.5	0.4	1.1	0.15	9.9	7.4
	8-29	13.7	7.3	5.39	1.9	0.6	1.3	0.21	9.2	6.3
P2	0-5	27.0	4.7	0.14	4.6	3.2	1.4	0.24	19.3	5.8
	5-25	18.3	16.5	1.60	14.9	9.9	4.9	0.68	21.9	7.3
P3	0-18	32.9	9.9	10.86	8.9	2.1	6.8	0.66	13.5	10.3
	18-40	21.1	7.4	2.73	4.6	1.2	3.4	0.45	10.2	7.5
G1	0-25	53.7	8.9	0.86	8.1	2.1	6.0	0.54	15.0	11.1
	25-60	25.2	13.3	2.59	10.7	3.8	6.9	0.49	21.7	14.0
G2	0-6	40.1	2.8	0.66	2.2	0.9	1.3	0.18	11.9	7.1
	6-16	32.7	5.9	1.99	3.9	1.9	2.1	0.33	12.1	6.4

Table S2: Abiotic soil properties: soil sampling 2001 and 2002.

Year	Site	Depth	Replicate	Soil moisture	pH($CaCl_2$)	C_t	$C_{carbonate}$	$C_{pyr}+C_{org}$	N_t	$(C_{pyr}+C_{org})/N_t$
		(cm)		(%)		----------(kg m^{-2})----------				
2001	**R**	0-8	1	14.9	7.4	0.9	0.1	0.8	0.03	28.8
			2	16.0	7.1	0.3	0.0	0.3	0.02	16.9
			3	18.6	6.5	4.7	0.0	4.7	0.11	41.8
		8-25	1	16.7	7.4	7.0	0.8	6.2	0.14	46.0
			2	16.0	7.5	8.3	0.9	7.4	0.17	43.0
			3	16.8	4.9	12.2	0.0	12.1	0.29	41.9
	A	0-10	1	24.2	7.0	3.9	0.6	3.3	0.21	15.8
			2	22.4	7.1	3.1	0.8	2.3	0.16	14.3
			3	24.0	7.1	3.9	1.3	2.6	0.18	14.7
		10-65	1	19.5	7.2	25.0	6.5	18.6	1.10	16.9
			2	16.9	7.3	21.7	8.9	12.8	0.80	15.9
			3	17.4	7.3	20.0	7.7	12.3	0.73	16.9
	H1	0-6	1	31.1	7.2	3.8	0.8	3.0	0.17	17.2
			2	32.6	7.1	3.4	0.8	2.6	0.16	15.6
			3	28.8	7.2	3.7	0.8	2.9	0.15	19.1
		6-20	1	21.6	7.3	5.9	4.4	1.5	0.23	6.3
			2	19.9	7.2	5.7	4.4	1.3	0.23	5.6
			3	18.2	7.2	6.7	4.4	2.3	0.19	11.9
	H2	0-9	1	26.2	7.2	2.4	0.4	2.0	0.18	11.3
			2	25.5	7.1	2.7	0.2	2.4	0.22	11.0
			3	26.7	7.1	2.9	0.3	2.7	0.25	11.0
		9-40	1	20.5	7.3	4.2	0.8	3.4	0.47	7.2
			2	19.9	7.2	3.7	0.8	2.9	0.47	6.2
			3	20.6	7.3	5.2	0.7	4.4	0.55	8.0
	H3	0-6	1	30.2	7.1	3.6	0.6	3.0	0.27	11.2
			2	27.7	7.1	4.4	1.1	3.3	0.30	10.8
			3	25.6	7.2	3.8	0.9	2.9	0.25	11.5
		6-25	1	19.9	7.2	6.2	3.3	2.9	0.40	7.2
			2	18.8	7.3	6.2	3.3	2.9	0.46	6.3
			3	15.6	7.3	7.0	3.3	3.7	0.35	10.7

Table S2: continued

Year	Site	Depth	Replicate	Soil moisture	pH($CaCl_2$)	C_t	$C_{carbonate}$	$C_{pyr}+C_{org}$	N_t	$(C_{pyr}+C_{org})/N_t$
		(cm)		(%)		----------(kg m^{-2})----------				
2001	**P1**	0-8	1	23.9	7.1	6.2	0.9	5.2	0.45	11.6
			2	24.0	7.0	6.6	0.9	5.6	0.50	11.1
			3	26.4	7.0	6.9	1.1	5.8	0.55	10.7
		8-29	1	16.4	7.3	9.9	3.6	6.2	0.41	15.0
			2	16.7	7.3	9.0	3.7	5.4	0.45	11.9
			3	17.4	7.3	8.9	3.7	5.3	0.45	11.7
	P2	0-5	1	36.5	7.0	3.9	0.2	3.6	0.24	15.2
			2	38.0	7.0	3.8	0.3	3.5	0.23	15.3
			3	35.9	7.0	3.7	0.3	3.4	0.23	14.9
		5-25	1	26.9	7.2	17.2	1.9	15.3	0.66	23.3
			2	23.5	7.2	16.7	2.5	14.2	0.59	24.0
			3	23.5	7.2	14.9	3.3	11.6	0.64	18.2
	P3	0-18	1	21.0	7.1	7.2	0.9	6.3	0.51	12.4
			2	23.2	7.1	8.0	1.0	7.0	0.58	12.2
			3	22.0	7.1	7.9	0.7	7.3	0.59	12.3
		18-40	1	17.8	7.3	7.2	1.6	5.7	0.51	11.2
			2	18.8	7.3	9.0	1.6	7.5	0.51	14.7
			3	16.7	6.9	7.3	1.6	5.7	0.67	8.6
	G1	0-25	1	20.0	7.1	6.4	0.8	5.6	0.34	16.7
			2	30.6	7.1	5.7	0.9	4.8	0.30	16.1
			3	28.5	7.2	5.9	0.9	5.1	0.25	19.9
		25-60	1	30.4	7.2	8.2	2.2	6.1	0.22	26.9
			2	23.5	7.0	11.2	3.2	7.9	0.52	15.2
			3	33.3	7.1	12.4	4.1	8.3	0.90	9.3
	G2	0-6	1	31.6	7.1	3.1	0.5	2.6	0.22	11.8
			2	27.0	7.1	2.7	0.9	1.8	0.18	9.8
			3	28.7	7.1	2.9	0.7	2.1	0.19	11.0
		6-16	1	22.1	7.3	5.0	1.9	3.1	0.27	11.5
			2	20.1	7.3	4.3	3.2	1.1	0.21	5.3
			3	19.1	7.3	4.0	2.5	1.5	0.20	7.4

Table S2: continued

Year	Site	Depth	Replicate	Soil moisture	pH($CaCl_2$)	C_t	$C_{carbonate}$	$C_{pyr}+C_{org}$	N_t	$(C_{pyr}+C_{org})/N_t$
		(cm)		(%)		----------(kg m^{-2})----------				
2002	**R**	0-8	1	11.8	4.4	0.9	0.1	0.8	0.03	28.8
			2	9.2	7.1	0.3	0.0	0.3	0.02	16.9
			3	5.1	7.2	4.7	0.0	4.7	0.11	41.8
		8-25	1	14.7	7.2	7.0	0.8	6.2	0.14	46.0
			2	12.5	7.3	8.3	0.9	7.4	0.17	43.0
			3	10.0	7.2	12.2	0.0	12.1	0.29	41.9
	A	0-10	1	20.7	7.0	3.9	0.6	3.3	0.21	15.8
			2	20.3	7.1	3.1	0.8	2.3	0.16	14.3
			3	19.7	7.1	3.9	1.3	2.6	0.18	14.7
		10-65	1	15.1	7.2	25.0	6.5	18.6	1.10	16.9
			2	14.5	7.3	21.7	8.9	12.8	0.80	15.9
			3	13.0	7.3	20.0	7.7	12.4	0.73	16.9
	H1	0-6	1	23.0	7.2	3.8	0.8	3.0	0.17	17.2
			2	24.7	7.1	3.4	0.8	2.6	0.16	15.6
			3	22.9	7.2	3.7	0.8	2.9	0.15	19.1
		6-20	1	22.5	7.3	5.9	4.4	1.5	0.23	6.3
			2	21.5	7.2	5.7	4.4	1.3	0.23	5.6
			3	22.9	7.2	6.7	4.4	2.3	0.19	11.9
	H2	0-9	1	21.4	7.3	2.4	0.4	2.0	0.18	11.3
			2	23.5	7.2	2.7	0.2	2.4	0.22	11.0
			3	24.6	7.3	2.9	0.3	2.7	0.25	11.0
		9-40	1	16.5	7.5	4.2	0.8	3.4	0.47	7.2
			2	18.6	7.4	3.7	0.8	2.9	0.47	6.2
			3	18.7	7.5	5.2	0.7	4.4	0.55	8.0
	H3	0-6	1	20.1	6.6	3.6	0.6	3.0	0.27	11.2
			2	25.2	6.9	4.4	1.1	3.3	0.30	10.8
			3	26.1	6.9	3.8	0.9	2.9	0.25	11.5
		6-25	1	19.1	6.9	6.2	3.3	2.9	0.40	7.2
			2	18.6	7.0	6.2	3.3	2.9	0.46	6.3
			3	19.2	6.9	7.0	3.3	3.7	0.35	10.7

Table S2: continued

Year	Site	Depth (cm)	Replicate	Soil moisture (%)	pH($CaCl_2$)	C_t	$C_{carbonate}$	$C_{pyr}+C_{org}$	N_t	$(C_{pyr}+C_{org})/N_t$
						----------(kg m^{-2})----------				
2002	**P1**	0-8	1	24.8	6.8	6.2	0.9	5.2	0.45	11.6
			2	27.8	6.6	6.6	0.9	5.6	0.50	11.1
			3	25.7	6.7	6.9	1.1	5.8	0.55	10.7
		8-29	1	16.2	7.1	9.9	3.6	6.2	0.41	15.0
			2	18.6	6.9	9.0	3.7	5.4	0.45	11.9
			3	18.7	6.9	8.9	3.7	5.3	0.45	11.7
	P2	0-5	1	30.3	7.0	3.9	0.2	3.6	0.24	15.2
			2	34.5	7.0	3.8	0.3	3.5	0.23	15.3
			3	33.0	7.0	3.7	0.3	3.4	0.23	14.9
		5-25	1	18.6	7.2	17.2	1.9	15.3	0.66	23.3
			2	20.3	7.2	16.7	2.5	14.2	0.59	24.0
			3	21.6	7.2	14.9	3.3	11.6	0.64	18.2
	P3	0-18	1	16.0	7.4	7.2	0.9	6.3	0.51	12.4
			2	16.0	7.3	8.0	1.0	7.0	0.58	12.2
			3	15.9	7.4	7.9	0.7	7.3	0.59	12.3
		18-40	1	14.1	7.4	7.2	1.6	5.7	0.51	11.2
			2	16.2	7.4	9.0	1.6	7.5	0.51	14.7
			3	16.0	7.4	7.3	1.6	5.7	0.67	8.6
	G1	0-25	1	32.4	6.7	6.4	0.8	5.6	0.34	16.7
			2	34.8	6.8	5.7	0.9	4.8	0.30	16.1
			3	39.9	6.9	5.9	0.9	5.1	0.25	19.9
		25-60	1	36.2	6.8	8.2	2.2	6.1	0.22	26.9
			2	37.8	6.8	11.2	3.2	7.9	0.52	15.2
			3	34.5	6.9	12.4	4.1	8.3	0.90	9.3
	G2	0-6	1	28.9	7.1	3.1	0.5	2.6	0.22	11.8
			2	29.6	7.1	2.7	0.9	1.8	0.18	9.8
			3	28.6	7.1	2.9	0.7	2.1	0.19	11.0
		6-16	1	22.5	7.3	5.0	1.9	3.1	0.27	11.5
			2	24.2	7.3	4.3	3.2	1.1	0.21	5.3
			3	21.2	7.3	4.0	2.5	1.5	0.20	7.4

Table S3: Biotic soil properties: soil sampling 2000.

Site	Depth	Replicate	C_{mic}(CFE)	N_{mic}	C_{mic}(SIR)	Arylsulphatase	Dehydrogenase	N-mineralization	Urease
	(cm)		----------(g m^{-2})----------			(g p-Nitrophenol h^{-1} m^{-2})	(g TPF 16 h^{-1} m^{-2})	(g N 7 d^{-1} m^{-2})	(g N 2 h^{-1} m^{-2})
R	0-8	1	5	0	19	1	8	4	1
		2	10	1	24	1	3	4	2
		3	20	1	25	2	5	4	2
	8-25	1	7	0	25	0	3	0	2
		2	4	0	26	0	2	0	2
		3	5	0	24	0	8	1	2
A	0-10	1	87	4	203	8	471	92	10
		2	50	5	233	4	402	49	9
		3	48	7	90	7	536	73	12
	10-65	1	25	2	1359	1	1312	40	1
		2	38	7	1519	12	868	43	2
		3	30	9	562	15	822	77	0
H1	0-6	1	44	5	90	7	429	82	30
		2	40	4	79	5	381	65	19
		3	40	5	78	5	416	58	10
	6-20	1	72	5	117	9	612	86	13
		2	43	1	109	6	503	68	9
		3	49	3	96	9	493	76	10
H2	0-9	1	70	9	149	12	555	104	10
		2	70	10	103	9	336	64	9
		3	67	10	121	8	301	50	11
	9-40	1	191	21	344	27	593	53	16
		2	150	23	330	34	598	97	21
		3	103	18	378	27	631	86	19
H3	0-6	1	52	4	81	6	273	44	11
		2	11	0	63	5	223	44	8
		3	41	6	70	5	294	45	10
	6-25	1	61	3	79	8	185	51	6
		2	69	12	46	9	175	45	7
		3	210	43	65	8	207	44	7

Table S3: continued

Site	Depth (cm)	Replicate	C_{mic}(CFE) ----------($g\ m^{-2}$)----------	N_{mic}	C_{mic}(SIR)	Arylsulphatase (g p-Nitrophenol $h^{-1}\ m^{-2}$)	Dehydrogenase (g TPF 16 $h^{-1}\ m^{-2}$)	N-mineralization (g N 7 $d^{-1}\ m^{-2}$)	Urease (g N 2 $h^{-1}\ m^{-2}$)
P1	0-8	1	43	1	77	10	164	17	7
		2	41	2	67	10	177	27	7
		3	43	2	69	8	144	27	6
	8-29	1	54	0	173	11	208	14	4
		2	90	2	161	15	204	17	4
		3	68	3	161	13	235	23	7
P2	0-5	1	57	8	98	5	323	54	11
		2	43	7	66	4	251	36	7
		3	36	8	89	4	337	54	9
	5-25	1	171	27	242	22	829	122	23
		2	118	9	246	16	789	136	22
		3	135	13	259	12	809	117	25
P3	0-18	1	263	38	447	19	1994	199	41
		2	231	30	276	19	1585	163	34
		3	193	30	277	20	1607	174	36
	18-40	1	117	14	627	28	714	94	14
		2	129	15	442	29	707	166	13
		3	163	18	359	30	652	89	14
G1	0-25	1	66	7	141	3	358	91	9
		2	121	14	115	11	493	79	12
		3	85	12	148	3	452	78	9
	25-60	1	166	18	157	9	684	64	17
		2	103	7	74	9	353	77	11
		3	141	11	93	11	390	74	14
G2	0-6	1	88	17	103	8	364	98	14
		2	99	18	124	8	569	100	17
		3	78	14	87	9	344	63	14
	6-16	1	164	26	168	22	627	106	24
		2	165	24	172	20	681	108	27
		3	153	24	163	21	569	100	23

Table S4: Biotic soil properties: soil sampling 2001 (DIN ISO methods: CFE, SIR, dehydrogenase activity, N-mineralization, NH_4-oxidation).

Site	Depth	Replicate	C_{mic}(CFE)	N_{mic}	C_{mic}(SIR)	Aryl-sulphatase	Dehydro-genase	N-mineralization	NH_4-oxidation	Phos-phatase	Urease
	(cm)		----------(g m^{-2})----------			(g p-Nitrophenol h^{-1} m^{-2})	(g TPF 16 h^{-1} m^{-2})	(g N m^{-2})	(g NO_2-N 6 h^{-1} ha^{-1})	(g Phenol 3 h^{-1} m^{-2})	(g N 2 h^{-1} m^{-2})
R	0-8	1	19	2	46	2	9	1	1	88	2
		2	24	3	46	3	8	1	1	96	2
		3	37	5	68	4	44	4	2	211	4
	8-25	1	7	0	53	1	4	0	0	19	2
		2	5	0	42	1	3	0	0	18	1
		3	3	0	35	0	2	0	0	11	0
A	0-10	1	71	12	155	22	825	2	53	537	10
		2	54	11	146	20	576	-1	55	373	6
		3	62	11	159	17	608	1	68	402	7
	10-65	1	231	79	1038	119	2339	13	221	2010	32
		2	241	61	956	74	1270	8	79	1106	20
		3	187	52	994	66	978	4	165	910	28
H1	0-6	1	64	13	175	17	842	1	92	516	12
		2	57	11	143	17	811	4	165	536	11
		3	45	10	118	11	441	6	96	449	7
	6-20	1	27	8	122	22	449	6	65	582	6
		2	32	8	166	26	429	6	69	571	5
		3	33	9	125	11	114	4	34	251	4
H2	0-9	1	68	7	159	45	258	5	65	471	6
		2	86	10	210	47	539	3	103	662	10
		3	100	12	156	58	629	3	89	671	11
	9-40	1	96	14	622	89	214	11	58	1024	6
		2	907	11	335	102	325	9	127	1082	8
		3	101	14	359	104	490	6	138	1191	11

Table S4: continued

Site	Depth	Replicate	C_{mic}(CFE)	N_{mic}	C_{mic}(SIR)	Aryl-sulphatase	Dehydro-genase	N-mineralization	NH_4-oxidation	Phos-phatase	Urease
	(cm)		----------(g m^{-2})----------			(g p-Nitrophenol h^{-1} m^{-2})	(g TPF 16 h^{-1} m^{-2})	(g N m^{-2})	(g NO_2-N 6 h^{-1} ha^{-1})	(g Phenol 3 h^{-1} m^{-2})	(g N 2 h^{-1} m^{-2})
H3	0-6	1	82	14	340	43	421	13	176	721	14
		2	98	16	357	42	512	10	289	782	14
		3	83	15	351	37	416	10	295	653	11
	6-25	1	99	9	295	43	195	12	127	504	7
		2	94	12	441	49	269	13	73	639	9
		3	86	8	492	47	186	10	62	521	7
P1	0-8	1	187	32	254	53	829	11	480	1335	27
		2	199	55	274	59	917	9	556	1373	30
		3	229	45	418	64	1245	12	640	1479	35
	8-29	1	169	32	300	47	286	6	317	916	12
		2	140	43	512	54	453	6	191	1033	14
		3	253	53	554	46	427	6	200	1149	14
P2	0-5	1	59	10	162	17	344	10	142	519	14
		2	63	11	120	17	317	10	164	521	15
		3	44	10	142	16	347	3	223	508	13
	5-25	1	82	16	225	34	390	18	256	1169	17
		2	112	14	335	30	241	16	200	943	15
		3	104	19	407	32	411	17	274	1253	16
P3	0-18	1	215	23	214	45	701	8	211	1167	19
		2	147	19	239	44	914	9	283	1265	21
		3	188	21	204	45	982	8	420	1438	28
	18-40	1	150	15	309	44	518	10	186	1021	12
		2	105	14	272	47	647	7	183	1226	13
		3	120	13	190	63	489	18	389	1301	13

Table S4: continued

Site	Depth (cm)	Replicate	C_{mic}(CFE)	N_{mic}	C_{mic}(SIR) (g m^{-2})	Aryl-sulphatase (g p-Nitrophenol h^{-1} m^{-2})	Dehydro-genase (g TPF 16 h^{-1} m^{-2})	N-mineralization (g N m^{-2})	NH_4-oxidation (g NO_2-N 6 h^{-1} ha^{-1})	Phos-phatase (g Phenol 3 h^{-1} m^{-2})	Urease (g N 2 h^{-1} m^{-2})
G1	0-25	1	35	5	85	9	213	4	51	290	6
		2	49	8	105	17	278	6	119	413	7
		3	44	5	87	11	226	5	71	293	6
	25-60	1	46	5	102	22	64	3	48	242	4
		2	112	25	141	43	296	3	111	543	9
		3	135	26	218	57	517	12	145	883	16
G2	0-6	1	92	14	165	26	317	9	104	568	14
		2	78	12	145	22	310	5	93	427	11
		3	95	12	264	25	305	5	89	534	10
	6-16	1	99	14	338	38	519	7	103	504	11
		2	68	11	274	31	489	3	69	399	8
		3	44	7	219	30	291	3	64	342	7

Table S5: Biotic soil properties: soil sampling 2002 (DIN ISO methods: CFE, SIR, dehydrogenase activity, N-mineralization, NH_4-oxidation).

Site	Depth	Replicate	C_{mic}(CFE)	N_{mic}	C_{mic}(SIR)	Aryl-sulphatase	Dehydro-genase	N-mineralization	NH_4-oxidation	Phos-phatase	Urease
	(cm)		----------(g m^{-2})----------			(g p-Nitrophenol h^{-1} m^{-2})	(g TPF 16 h^{-1} m^{-2})	(g N m^{-2})	(g NO_2-N 6 h^{-1} ha^{-1})	(g Phenol 3 h^{-1} m^{-2})	(g N 2 h^{-1} m^{-2})
R	0-8	1	1	0	30	0	0	1	0	13	1
		2	14	3	41	2	11	2	1	113	3
		3	16	3	20	2	12	1	1	95	3
	8-25	1	2	0	45	0	0	0	2	11	1
		2	7	1	42	0	1	0	4	32	5
		3	5	0	37	0	0	0	1	32	2
A	0-10	1	34	8	148	6	67	2	129	262	5
		2	37	7	143	6	49	2	133	265	4
		3	43	8	150	5	59	3	130	244	3
	10-65	1	184	34	985	37	144	14	407	1183	19
		2	105	19	929	40	77	15	91	723	12
		3	127	15	944	33	44	9	149	769	12
H1	0-6	1	15	3	157	3	35	1	88	168	3
		2	15	2	128	2	16	0	68	121	2
		3	19	3	109	2	66	0	123	186	3
	6-20	1	37	8	123	3	81	3	336	465	7
		2	35	6	170	3	90	4	270	401	6
		3	28	5	132	5	89	1	219	354	6
H2	0-9	1	54	12	80	40	192	2	450	682	8
		2	48	10	54	50	141	7	161	560	4
		3	44	9	62	45	107	7	217	512	4
	9-40	1	74	12	194	81	153	7	250	1208	7
		2	59	10	147	92	69	9	152	858	6
		3	69	11	237	97	67	16	416	1009	6

Table S5: continued

Site	Depth (cm)	Replicate	C_{mic}(CFE) ----------(g m^{-2})----------	N_{mic}	C_{mic}(SIR)	Aryl-sulphatase (g p-Nitrophenol h^{-1} m^{-2})	Dehydro-genase (g TPF 16 h^{-1} m^{-2})	N-mineralization (g N m^{-2})	NH_4-oxidation (g NO_2-N 6 h^{-1} ha^{-1})	Phos-phatase (g Phenol 3 h^{-1} m^{-2})	Urease (g N 2 h^{-1} m^{-2})
H3	0-6	1	23	5	119	9	56	3	403	223	5
		2	62	12	138	14	168	2	856	434	10
		3	58	11	141	13	108	4	884	483	10
	6-25	1	50	8	117	18	17	7	365	311	5
		2	43	11	176	28	74	6	582	443	9
		3	70	12	206	28	89	10	797	578	9
P1	0-8	1	165	33	136	27	640	6	2193	1289	29
		2	188	33	181	30	819	-2	3762	1408	38
		3	141	22	156	28	447	9	2211	1394	27
	8-29	1	110	18	145	31	208	5	1835	1094	24
		2	201	36	258	51	473	5	5017	2500	37
		3	145	23	289	36	522	6	1944	1971	21
P2	0-5	1	38	4	53	26	133	3	822	326	9
		2	46	4	55	23	211	2	917	359	11
		3	48	4	60	29	194	2	878	424	11
	5-25	1	51	6	44	68	139	6	1246	525	13
		2	58	5	59	56	84	11	972	521	10
		3	70	3	83	77	176	9	1252	703	13
P3	0-18	1	106	23	135	82	579	5	982	1036	15
		2	113	22	107	89	541	7	1268	1055	17
		3	100	22	147	75	444	5	905	961	14
	18-40	1	107	23	184	98	292	10	656	1118	11
		2	80	22	221	93	343	13	971	1226	12
		3	94	24	244	103	356	11	533	1124	11

Table S5: continued

Site	Depth	Replicate	C_{mic}(CFE)	N_{mic}	C_{mic}(SIR)	Aryl-sulphatase	Dehydro-genase	N-mineralization	NH_4-oxidation	Phos-phatase	Urease
	(cm)		----------(g m^{-2})----------			(g p-Nitrophenol h^{-1} m^{-2})	(g TPF 16 h^{-1} m^{-2})	(g N m^{-2})	(g NO_2-N 6 h^{-1} ha^{-1})	(g Phenol 3 h^{-1} m^{-2})	(g N 2 h^{-1} m^{-2})
G1	0-25	1	49	10	52	14	90	8	497	556	9
		2	68	12	67	13	135	10	540	473	8
		3	76	17	125	17	241	14	791	654	11
	25-60	1	129	25	158	29	278	19	1499	1159	19
		2	160	31	182	45	277	26	1867	1297	20
		3	125	25	162	36	392	24	1452	1082	18
G2	0-6	1	50	10	159	9	55	3	368	346	6
		2	60	12	150	11	97	8	298	458	9
		3	61	13	105	12	121	3	788	541	8
	6-16	1	70	12	136	35	58	7	842	453	7
		2	93	18	116	34	100	7	1110	667	13
		3	89	18	90	40	75	6	758	652	9

Table S6: Microbial potentials in 0-30 cm depth during the study period (2001 and 2002 also solely using DIN ISO methods).

Site	Replicate	2000	2001	2002	2001 DIN ISO	2002 DIN ISO
R	1	0.01	0.00	0.01	0.03	0.01
	2	0.01	0.00	0.05	0.03	0.03
	3	0.02	0.03	0.02	0.05	0.01
A	1	0.31	0.40	0.38	0.40	0.24
	2	0.30	0.31	0.33	0.31	0.21
	3	0.21	0.30	0.34	0.31	0.22
H1	1	0.40	0.32	0.29	0.34	0.19
	2	0.29	0.34	0.30	0.36	0.20
	3	0.30	0.24	0.24	0.24	0.15
H2	1	0.38	0.32	0.29	0.33	0.17
	2	0.35	0.32	0.24	0.31	0.15
	3	0.33	0.35	0.29	0.31	0.19
H3	1	0.25	0.47	0.25	0.50	0.18
	2	0.23	0.55	0.38	0.58	0.25
	3	0.49	0.51	0.44	0.56	0.31
P1	1	0.11	0.67	0.61	0.55	0.41
	2	0.14	0.82	0.90	0.63	0.62
	3	0.13	0.97	0.72	0.82	0.51
P2	1	0.52	0.42	0.23	0.42	0.17
	2	0.40	0.44	0.26	0.45	0.21
	3	0.43	0.48	0.30	0.47	0.23
P3	1	0.73	0.43	0.44	0.41	0.27
	2	0.60	0.40	0.44	0.38	0.28
	3	0.59	0.44	0.45	0.41	0.27
G1	1	0.15	0.04	0.14	0.07	0.10
	2	0.19	0.09	0.18	0.11	0.14
	3	0.17	0.08	0.24	0.10	0.19
G2	1	0.89	0.71	0.60	0.72	0.39
	2	0.92	0.54	0.69	0.55	0.45
	3	0.82	0.48	0.62	0.48	0.38

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