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• *Radiocesium – Forest soils – Humus – Bavaria*

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A Novel Approach to Monitoring the Cs-137 Contamination of Forest Soils in Bavaria, Germany

Neuer Ansatz zur Überwachung der Cs-137-Belastung von Waldböden in Bayern, Deutschland

With 8 Figures and 2 Tables

Regarding the radioactive fission product Cs-137, particularly forest soils are hot spots of long-term contamination. Previous studies have indicated that monitoring should take account of the exceptional role of humus for Cs-137 mobility and bioavailability to effectively evaluate contamination patterns and to enhance future protection strategies in forests. As official programmes in Bavaria lack such considerations, a new monitoring project has been established together with the Bavarian State Ministry of the Environment and Public Health, focussing on humus-controlling landscape parameters (relief, vegetation etc.) as crucial core criteria. Comprising a total of 48 sites, the project provides a solid base for future research. Both the site selection process and first results are presented here.

1. Introduction

As a result of the Chernobyl nuclear accident in 1986, vast amounts of the toxic radioactive contaminant Cs-137 (half life: 30.17 yrs) have been deposited across Europe. Because of its pronounced similarity in ionic diameter and hydration energy, the monovalent alkali metal cesium is an effective chemical substitute for the essential nutrient potassium (*Kruyts* et al. 2000, *Shaw* and *Bell* 1994, *Schaller* et al. 1993, *van Voris* et al. 1990). In general, its plant availability in soils negatively correlates with clay content and positively with organic matter content (*de Koning* et al. 2007, *Kruyts* et al. 2000, *Maes* et al. 1999, *Hird* et al. 1996, *Comans* et al. 1991, *Andolina* and *Guillitte* 1990, *Sweeck* et al. 1990, *van Voris* et al. 1990, *Cremers* et al. 1988). Hence, organic layers represent an important and persistent Cs-137 sink and source within the dynamic system of matter cycles (*Shcheglov* et al. 2001). Particularly in forest ecosystems, the complex interaction of poorly decomposable litter, low pH values, insufficient potassium supply and reduced activity of soil organisms encourages the development of massive organic layers resulting in an effective physicochemical barrier against downward cesium dislocation into mineral soil horizons (*Konopleva* et al. 2009, *Zhiyanski* et al. 2008, *Kruyts* and *Delvaux* 2002, *Völkel* 2002, *Shcheglov* et al. 2001, *Völkel* 1998, *Andolina* and *Guillitte* 1990). Moreover, other than in agricultural soils (periodical ploughing), the translocation of cesium in forest soils exclusively depends on natural processes. Hence, forest soils feature a completely different long-term contamination potential. Compared to an average of approx. 37 Bq kg^{-1} in agricultural soils (Bayerisches Landesamt für Umwelt 2006a), strikingly high activity levels are still prevalent in the organic layers of forest soils, particularly in Of- and Oh-horizons of low mountain and alpine regions with activities typically ranging between 1,000 and 4,000 Bq kg^{-1} in Bavaria, Germany (*Völkel* and *Leopold* 2006, *Völkel* 2002, *Pietrzak-Flis* et al. 1996, *Kammerer* et al. 1994). This results in persistently high Cs-137 activities in certain fungi and game species (esp. *Xerocomus badius* and *Sus scrofa;* Bayerisches Landesamt für Umwelt 2006b) due to the specific interrelation of metabolic/dietary characteristics and soil contamination depths (*Hohmann* and *Huckschlag* 2005, *Stemmer* et al. 2005, *Putyrskaya* et al. 2003, *Steiner* et al. 2002, *Rühm* et al. 1998, *Kammerer* et al. 1994).

2. Objectives

The preceding facts demonstrate that the specific distribution of total Cs-137 contents in forest soils, represented as activity per mass (Bq kg^{-1}) or area (Bq m^{-2}), significantly depends on the composition of its organic layers and thus on the environmental landscape parameters which influence their accumulation and decomposition. The necessity of incorporating the aspect of landscape ecology into long-term radiocesium monitoring approaches has been confirmed by numerous publications dealing with radiocesium mapping and surveying, among others by *Dubois* et al. (2004) and *Bossew* (2003). Sampling approaches based on landscape classifications are found to by far outweigh grid distribution based sampling or the exclusive selection of long-term stability sites in this context (*Bossew* 2003). The International Atomic Energy Agency (IAEO) supports this position and criticises the overall insufficient consideration in state-of-the-art monitoring approaches (*Bossew* 2003). Particularly with regard to suspected global warming and its potential effects on soil-to-plant transfer of nutrients, the dynamics of radionuclides in forest soils are supposed to be of growing interest in future (*Dowdall* et al. 2008).

In the case of Bavaria, only 8 special radionuclide long-term monitoring sites have been continuously maintained by the Bavarian Environment Agency since 1990 (*Schilling* et al. 2005). Although reflecting different deposition regimes and ecological backgrounds, both the number and distribution of these sites is critical with regard to an elaborate representation of the entire 2.56 mill. ha of forest in Bavaria. Against this background, a new comprehensive survey network has been established in cooperation with the Bavarian State Ministry of the Environment and Public Health, to further enhance the value of long-term governmental radioprotection strategies in forest ecosystems.

Comprehensive studies on this issue have been carried out by *Völkel* (2002, 1998, 1995) and summarised in a default guideline which defines both the required site distribution strategy as well as sampling standards for such a monitoring (*Völkel* and *Leopold* 2006). The guideline's aim is to facilitate the comparable determination of the general variability and vertical distribution of Cs-137 activities (Bq kg^{-1}; Bq m^{-2}) in forest soils of all different landscape types (natural/seminatural) of Bavaria by an identical

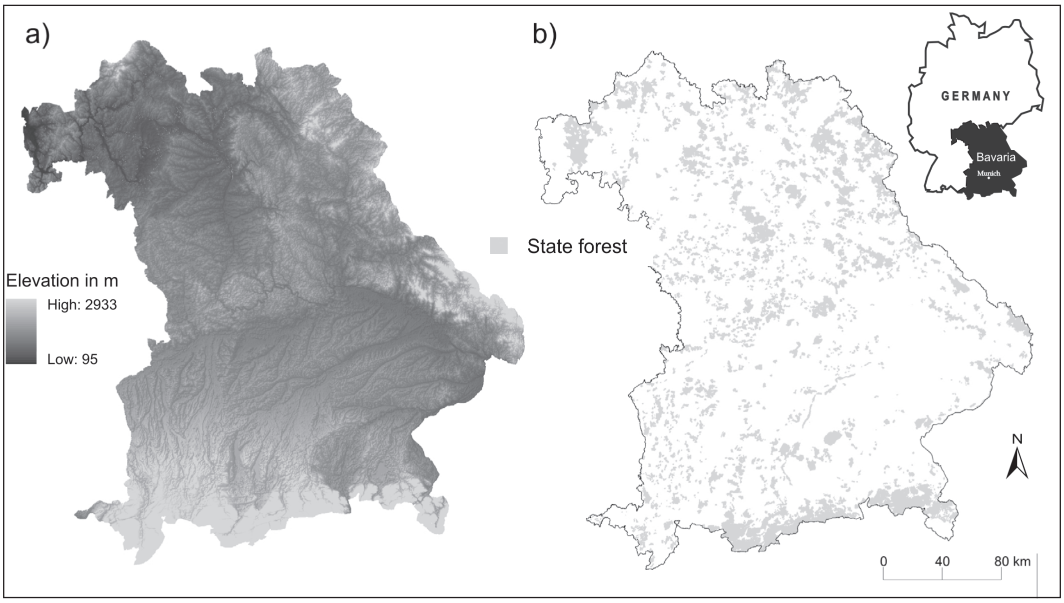


Fig. 1 Study area: a) Digital elevation model of Bavaria based on NASA SRTM data (spatial resolution: 90 x 90 m); b) Distribution of Bavarian state forest stands (source: Bavarian State Forestry 2007)
Untersuchungsgebiet: a) Digitales Höhenmodell von Bayern basierend auf NASA-SRTM-Daten (Auflösung: 90 x 90 m); b) Verbreitung der bayerischen Staatswälder (Quelle: Bayerische Staatsforsten 2007)

sampling procedure. The distribution strategy defines the number of required monitoring sites in general as well as the distribution across several stand, inclination and altitude types. The sampling standards define a completely novel approach for a horizon-based site sampling in case of a renewed nuclear accident (site dimension, characterisation/classification of organic layer thicknesses, number of samples, extraction, preparation, recording, sampling depths). By assuring a systematic sampling of different humus thicknesses, this procedure will not only be capable of rendering the average pollution within the several landscapes but, moreover, will be able to identify the prevailing Cs-137 variety as well as characteristic hot spots. Although designed expecially for forest ecosystems of Bavaria, this basic approach can be transferred to any particular environment of interest, making it a very valuable tool for radio-ecological monitoring in forest ecosystems worldwide.

The concept presented in this paper primarily transfers these standards into a practical GIS-based site selection routine. Besides the detailed description of the fundamental selection process, a short characterisation of the installed monitoring sites and first results on the general Cs-137 distribution pattern across Bavarian forest soils are presented here. The resulting monitoring inventory offers the unique possibility of elaborately surveying the Cs-137 contamination throughout the entire Bavarian state territory. Further tasks will be to characterise and quantify future contamination risks in subsequent investigations by comprehensively evaluating the observed Cs-137 contamination patterns via geostatistical analysis with regard to the underlying site specific ecological and edaphic parameters.

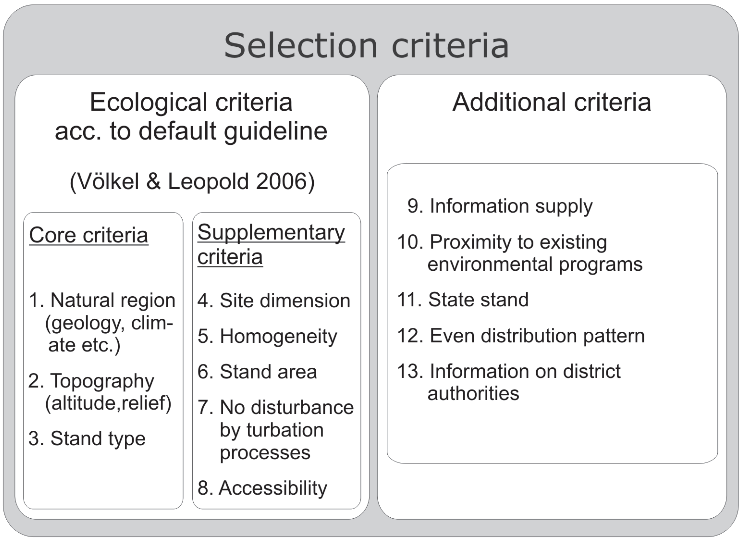


Fig. 2 Selection criteria. – Left: Scientific criteria as listed in the default guideline of *Völkel* and *Leopold* (2006), included because of their ecological relevance in influencing either humus variability or the contamination risk of certain species. The criteria which have the strongest influence on humus variability are considered as core criteria (natural region, topography/altitude, forest stand type/composition). Right: Additional set of organisational and technical criteria, introduced in order to improve the actual monitoring implementation (general performance, information value) / *Auswahlkriterien. – Linke Seite: Kriterien auf wissenschaftlicher Grundlage der Handlungsvorgabe nach Völkel und Leopold (2006), die vornehmlich aufgrund ihrer landschafts-/radioökologischen Relevanz hinsichtlich der Humusvariabilität, aber auch hinsichtlich des Kontaminationsrisikos diverser Arten berücksichtigt werden. Die Kriterien mit dem größten Einfluss auf die Humusvariabilität werden als sogenannte Kernkriterien bezeichnet (Naturräumliche Einheit, Topographie/Höhenlage, Bestandsart/-zusammensetzung). Rechte Seite: Zusätzliche Gruppe an organisatorischen und technischen Kriterien, die die tatsächliche Umsetzung des Monitoringprogramms erleichtern sollen (Durchführung im Allgemeinen, Informationsgehalt).*

3. Study Area

Bavaria is located in the southeast of Germany and is characteristically confined by the high mountain ranges of the Alps towards the Republic of Austria to the South and by the low mountain ranges of the Bavarian Forest towards the East (Chech Republic). These two mountain ranges together with the escarpment landscape of the Swabian Alb form distinctive contrasts to the lowland and basin character along the main drainage line of the Danube river valley (*Fig. 1a*). The topic of Cs-137 contamination of forest soils plays a very important role in this area for two main reasons. On the one hand, in 1986 Bavaria experienced the highest radionuclide deposition far beyond the rest of Germany. On the other hand, Bavaria is the one German state with the highest percentage of forested areas. A total of 2.56 mill. ha is covered with forests, 30.1 % of which are state forests (*Fig. 1b*; Bayerische Landesanstalt für Wald und Forstwirtschaft 2004). It is on these that the study is primarily focussed.

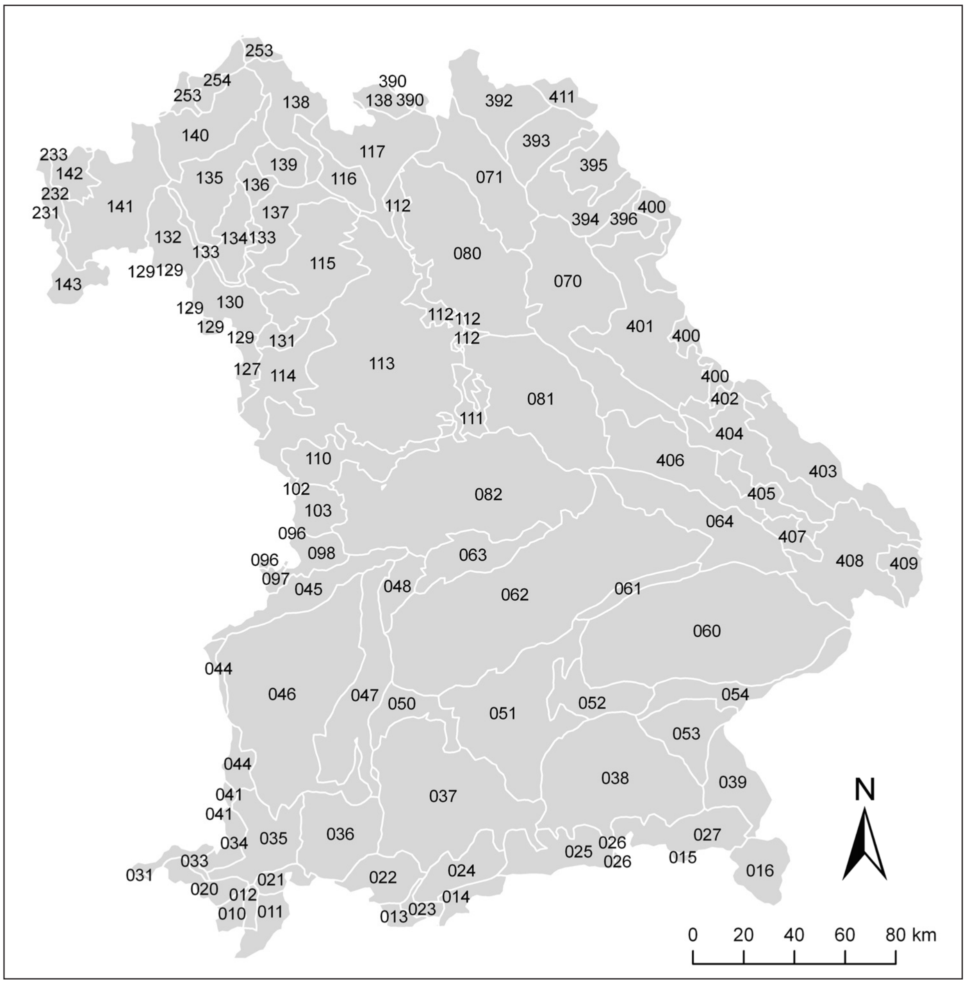


Fig. 3 Natural regions of Bavaria according to *Meynen* et al. (1962). The names of the regions are given in *Table 1* (Numbers 010-411). / *Naturräumliche Einheiten in Bayern nach Meynen et al. (1962). Die zugehörigen Bezeichnungen der Einheiten können Tabelle 1 entnommen werden (Nr. 010-411).*

4. Materials and Methods

4.1 Pre-selection

4.1.1 Selection criteria

Originally, the site selection was based on a specifically designed default guideline for the monitoring of Cs-137 in forest soils by *Völkel* and *Leopold* (2006) as explained in Section 2. The data sets used for site selection hence primarily focus on the humus-controlling parameters landscape type, stand composition, inclination and altitude. At the same time, the approach requires a comprehensive survey design additionally considering various organisational criteria, which prepare and facilitate future tasks of implementation and

Tab 1 Specific ecological characteristics of the 95 natural regions as defined by *Meynen* et al. (1962). Altitude parameters were derived from SRTM data including the percentage of each of the three specified altitude classes with respect to the total area of the region; the percentage of state stand area is also related to the region's total area; mean annual precipitation values according to *Meynen* et al. (1962). / *Ausgewählte landschaftsökologische Parameter der 95 naturräumlichen*

Natural region		Altitude m a.s.l.				Altitude classes			State forest area (%)	Precipitation (mm/a)	
N°	Title	Min	Max	Ø	St. dev.	Class 1 (%)	Class 2 (%)	Class 3 (%)		Min	Max
010	Hinterer Bregenzer Wald	729	2066	1372	358	0	92	8	19	1800	> 2500
011	Allgäuer Hochalpen	763	2583	1586	479	0	88	12	9	1700	> 2500
012	Oberstorfer Becken	724	1336	973	155	0	95	5	0	1500	1800
013	Wettersteingebirge	724	2933	1696	562	0	15	85	87	1300	> 2500
014	Karwendelgebirge	746	2320	1485	430	0	33	67	78	1400	2200
015	Loferer u. Leoganger Alpen	657	1606	1084	251	0	37	63	63	1600	2200
016	Berchtesgadener Alpen	453	2587	1464	580	0	38	61	28	1400	> 2500
020	Vorderer Bregenzer Wald	475	1807	1125	367	0	58	42	8	1600	> 2500
021	Vilser Gebirge	730	1814	1232	289	0	24	76	11	1400	2100
022	Ammergebirge	628	2150	1336	410	0	27	73	51	1400	2200
023	Niederwerdenfelser Land	637	1676	1066	253	0	48	52	46	1200	1700
024	Kocheler Berge	597	2042	1285	399	0	47	53	35	1600	2300
025	Mangfallgebirge	460	1873	1141	393	0	38	62	43	1500	> 2500
026	Kufsteiner Becken	458	618	505	34	88	12	0	1	1300	1400
027	Chiemgauer Alpen	454	1844	1107	373	0	62	37	61	1200	> 2500
031	Bodenseebecken	390	471	428	22	100	0	0	1	750	1400
033	Westallgäuer Hügelland	416	1025	685	156	16	84	0	2	1000	1800
034	Adelegg	680	1246	963	159	0	86	14	12	1500	2000
035	Iller-Vorberge	622	1251	921	174	0	95	5	7	1100	2100
036	Lech-Vorberge	655	1069	854	113	0	100	0	5	1000	1500
037	Ammer-Loisach-Hügelland	526	993	757	133	0	100	0	7	850	1600
038	Inn-Chiemsee-Hügelland	414	932	668	147	31	69	0	3	850	1600
039	Salzach-Hügelland	364	830	586	129	57	43	0	4	950	1700
041	Riß-Aitrach-Platten	604	805	695	53	0	100	0	5	800	1600
044	Unteres Illertal	460	771	609	87	21	79	0	3	700	1100
045	Donauried	380	491	436	32	100	0	0	3	630	700
046	Iller-Lech-Schotterplatten	403	925	662	150	26	74	0	11	650	1200
047	Lech-Wertach-Ebenen	390	766	574	107	32	68	0	0	600	1000
048	Aindlinger Terrassentreppe	380	554	466	50	90	10	0	10	670	770
050	Fürstenfeldbrucker Hügelland	510	749	629	69	0	100	0	5	800	1000
051	Münchener Ebene	399	759	580	104	37	63	0	13	680	1300
052	Isen-Sempt-Hügelland	406	651	531	69	37	63	0	4	680	950
053	Alzplatte	393	659	523	75	50	50	0	0	850	1400
054	Unteres Inntal	258	501	392	56	100	0	0	11	720	870
060	Isar-Inn-Hügelland	302	564	433	76	94	6	0	1	700	880
061	Unteres Isartal	336	464	389	32	100	0	0	4	670	700
062	Donau-Isar-Hügelland	330	589	459	75	83	17	0	3	590	800
063	Donaumoos	343	436	389	27	100	0	0	1	620	680
064	Dungau	295	410	347	29	100	0	0	0	590	850
070	Oberpfälzisches Hügelland	313	733	529	118	89	11	0	17	590	1000
071	Obermainisches Hügelland	265	597	425	93	96	4	0	9	640	1000
080	Nördliche Frankenalb	280	655	468	108	68	32	0	9	660	> 950
081	Mittlere Frankenalb	326	654	489	94	62	38	0	8	560	> 900
082	Südliche Frankenalb	325	666	496	98	55	45	0	12	600	> 850
096	Albuch und Härtsfeld	482	645	568	45	2	98	0	45	900	1050
097	Lonetal-Flächenalb	439	543	488	29	86	14	0	5	670	750
098	Riesalb	399	622	509	64	53	47	0	9	650	720
102	Vorland d. östl. Schwäbischen Alb	428	536	482	30	95	5	0	0	680	920

sampling (site dimension, accessibility etc.). *Figure 2* summarises all relevant criteria.

The concept of landscape regionalisation is a key element of the selection process. As the defined

Einheiten nach Meynen et al. (1962). Alle Höhenangaben, einschließlich des prozentualen Flächenanteils der drei im Vorfeld definierten Höhenklassen innerhalb einer naturräumlichen Einheit, wurden auf Basis von SRTM-Datensätzen ermittelt; der prozentuale Flächenanteil an Staatsforsten bezieht sich ebenfalls auf die Gesamtfläche der entsprechenden naturräumlichen Einheit; die mittleren Jahresniederschlagssummen wurden Meynen et al. (1962) entnommen.

Natural region		Altitude m a.s.l.				Altitude classes			State forest area (%)	Precipitation (mm/a)	
N°	Title	Min	Max	Ø	St. dev.	Class 1 (%)	Class 2 (%)	Class 3 (%)		Min	Max
103	Ries	398	538	467	40	99	1	0	0	580	720
110	Vorland d. südl. Frankenalb	382	681	523	83	92	8	0	2	630	750
111	Vorland d. mittl. Frankenalb	361	578	465	61	98	2	0	3	650	820
112	Vorland d. nördl. Frankenalb	247	459	351	60	100	0	0	8	650	870
113	Mittelfränkisches Becken	229	548	389	92	98	2	0	14	560	790
114	Frankenhöhe	292	562	427	78	89	11	0	9	600	830
115	Steigerwald	224	504	364	81	100	0	0	15	570	790
116	Haßberge	225	522	374	86	100	0	0	28	620	720
117	Itz-Baunach-Hügelland	223	495	357	78	100	0	0	9	580	800
127	Hohenloher und Haller Ebene	293	525	409	66	100	0	0	1	660	870
129	Tauberland	224	452	337	65	100	0	0	2	570	750
130	Ochsenfurter u. Gollachgau	186	427	307	70	100	0	0	1	550	670
131	Windsheimer Bucht	292	435	364	42	100	0	0	0	570	670
132	Marktheidenfelder Platte	158	398	278	70	100	0	0	8	600	660
133	Mittleres Maintal	147	358	251	59	100	0	0	0	545	600
134	Gäuplatten im Maindreieck	184	344	264	47	100	0	0	1	550	620
135	Wern-Lauer-Platte	159	426	291	77	100	0	0	5	530	690
136	Schweinfurter Becken	179	323	254	40	100	0	0	0	540	600
137	Steigerwald Vorland	187	400	284	57	100	0	0	2	530	850
138	Grabfeldgau	224	537	381	90	99	1	0	4	600	730
139	Hesselbacher Waldland	219	431	325	61	100	0	0	9	600	730
140	Südrhön	157	711	405	145	97	3	0	17	520	1000
141	Sandsteinspessart	118	597	357	138	96	4	0	29	600	1090
142	Vorderer Spessart	115	436	274	91	100	0	0	3	640	1000
143	Sandsteinodenwald	117	552	333	125	97	3	0	0	700	900
231	Rheinheimer Hügelland	117	236	173	32	100	0	0	0	650	750
232	Untermainebene	95	215	153	32	100	0	0	0	520	650
233	Ronneburger Hügelland	124	274	198	43	100	0	0	0	590	800
253	Vorder-u. Kuppenrhön	262	715	488	130	70	30	0	19		
254	Lange Rhön	393	931	662	154	7	93	0	11		
390	Südl. Vorland d. Thür. Waldes	320	531	426	61	95	5	0	42	600	930
392	Nordwestlicher Frankenwald	337	801	564	131	16	84	0	26	550	1150
393	Münchberger Hochfläche	357	739	551	107	8	92	0	1	550	1050
394	Hohes Fichtelgebirge	413	1042	727	177	1	98	0	44	600	1250
395	Selb-Wunsiedler Hochfläche	441	708	573	77	4	96	0	12	580	1000
396	Naab-Wondreb-Senke	436	607	522	49	36	64	0	16	580	900
400	Hinterer Oberpfälzer Wald	382	937	670	154	4	96	0	33	600	980
401	Vorderer Oberpfälzer Wald	361	776	567	119	41	59	0	8	650	850
402	Cham-Further Senke	354	657	482	76	94	6	0	1	670	900
403	Hinterer Bayerischer Wald	441	1441	927	282	1	79	20	19	900	1850
404	Regensenke	362	907	632	157	33	67	0	2	700	1200
405	Vorderer Bayerischer Wald	339	1114	732	217	6	91	3	15	950	1450
406	Falkensteiner Vorwald	310	751	529	127	65	35	0	2	650	1200
407	Lallinger Winkel	311	617	460	87	94	6	0	1	850	1200
408	Passauer Abteiland u. Neuburger Wald	252	1014	626	204	67	33	0	5	800	1200
409	Wegscheider Hochfläche	476	952	708	131	0	100	0	2	900	1150
411	Mittelvogtländ. Kuppenland	415	671	543	74	12	88	0	1	580	750

units share the same set of abiotic parameters, they provide a general base for approximating the spatial variability of humus types and should each be represented by their own set of monitoring sites (*Völkel* and *Leopold* 2006). Several approaches can be used for this purpose. One of them is the concept of natural regions (*Fig. 3*) as defined by the German landscape classification of *Meynen* et al. (1962), for which the studies of *Völkel* (2002) and *Völkel* and *Leopold* (2006) demonstrate a correlation in terms of cesium variability. The categorisation focuses particularly on geological, geomorphological and climatological differences. The typical altitude and precipitation ranges for the 95 subdivisions demonstrate the huge ecological landscape variety in Bavaria, stretching from less variable lowland units to low and high mountain regions with prominent variations of altitude and precipitation (*Tab. 1*). This again stresses the importance of an initial regionalisation.

To tackle the intrinsic problem of generalisation, however, the crucial landscape parameters of relief and forest stand properties have to be investigated separately. As humus thickness and variability increase with increasing altitude and precipitation, lowland regions (< 500 m) get two and low mountain and high mountain regions (> 500 m) four sites each in order to depict char-

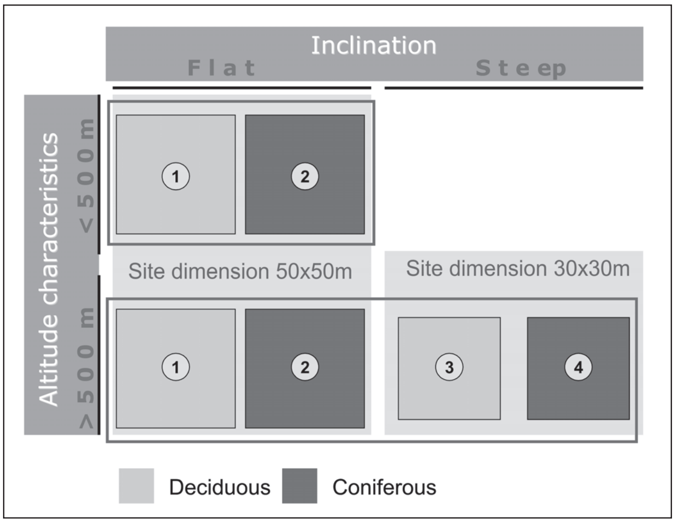


Fig. 4 Compulsory site procedure. – Both the number and the basic requirements for the monitoring sites of each natural region vary by their landscape character. Lowland regions (<500 m) are covered by two monitoring sites, both of them located in flat/low terrain. Low mountain and alpine regions (> 500 m) are covered by four monitoring sites, two of them located in flat/low terrain and two of them on steep slopes. Site dimensions are 50 x 50 m in flat/low terrains and 30 x 30 m on steep slopes. Additionally, each set of monitoring sites has to represent an equal share of deciduous and coniferous stand types.
Vorgeschriebenes Flächenkonzept. – Sowohl die Anzahl als auch die abzudeckende Grundausstattung der Monitoringflächen jeder naturräumlichen Einheit richten sich nach deren jeweiligem Landschaftscharakter. Einheiten mit Flachlandcharakter (< 500 m) werden mit 2 Monitoringflächen in flachem Gelände abgedeckt. Mittel- und Hochgebirgseinheiten (>500 m) erhalten insgesamt 4 Monitoringflächen, von denen jeweils 2 in flachem und 2 in steilem Gelände positioniert werden. Die Beprobungsfläche in flachem Gelände beträgt 50 x 50 m, in steilem Gelände 30 x 30 m. Zudem muss jede Neigungsklasse (flach, steil) sowohl einen Laub- als auch einen Nadelwaldstandort repräsentieren.

acteristic variations. Small-scale variations of inclination are also considered by incorporating a distinction between flat and steep slopes at values of 10-15° following *Bastian* (1999) and Ad-hoc-AG Boden (2005). Furthermore, the approach accounts for the major effect of forest stand properties on humus composition by distributing the monitoring sites equally in both deciduous and coniferous stands. For the selection process, those core criteria are interconnected to a strict distribution scheme (*Fig. 4*), which assures that the sites properly reflect the ecological variety within each natural region.

In low and high mountain regions the site area is set to 30 x 30 m. Due to generally lower spatial variability, dimensions of 50 x 50 m are applied in lowlands in order to capture the whole range of thicknesses adequately (*Völkel* and *Leopold* 2006). The sites have to be homogeneous concerning the core criteria and are disqualified for further investigations if they show significant disturbances due to mechanical turbation processes (no wind throw and uprooting, no forestry measures within the last 20 years) in order to avoid a misinterpretation of the natural translocation velocity in the investigated soil profiles (*Völkel* and *Leopold* 2006). As it is a major goal to optimise the detection of high contamination risks, extensive forest stands of at least 12 ha should be focused on (*Völkel* and *Leopold* 2006), since forest wildlife browsing districts will then commonly exclude less contaminated agricultural surroundings (*Kiefer* et al. 1996, *Fielitz-Vogl* 1992). For pragmatic purposes unobstructed accessibility should be consequently promoted. In order to assure long-term research permissions, the selection should be limited to state forests (governmental cooperation). Despite focussing on ecological representativeness, a regularly spaced distribution has to be attempted in order to avoid large survey gaps and to meet the official AVV-IMIS standards (AVV-IMIS: *Allgemeine Verwaltungsvorschriften zum Integrierten Mess- und Informationssystem* / General administrative regulations for the integrated monitoring and information system; Bundesministerium für Justiz 2006). To establish the concept as an effective administrative instrument, it should be linked to already existing (radioactivity) monitoring programmes, especially to the federal IMIS sites for the continuous monitoring of the ambient dose rate of the air operated by the Federal Office for Radiation Protection (BfS) as well as to the Bavarian soil radioactivity monitoring sites of the Bavarian Environment Agency (LfU). The proximity to other ecological monitoring stations, e.g. by the LfU long-term soil monitoring programme and GRABEN project (GRABEN: *Wissenschaftliche Grundlagen für den Vollzug der Bodenschutzgesetze* / Scientific fundamentals for the implementation of the soil protection laws), which will be helpful for interpreting the sites in a comprehensive ecological context. For further optimisation, the degree of information supply provided by data sets such as geological, soil or vegetation maps should be considered. Finally, the data set is extended by the relevant contact information on the responsible district authorities.

4.1.2 Data base

In a next step, the specified selection criteria were transferred to digital data sets and interconnected within a common GIS data base using ArcMap Version 9.3 by ESRI ArcGIS. GIS applications have by now established as a common tool for data management and analysis in the fields of spatial planning and radioprotection (*Bossew* 2003, *de Nooijer* and *Chabanyuk* 2002, *Deville-Cavelin* et al. 2002, *Kolejka* 2002b, *Siegel* and *Palko* 2002, *de Cort* et al. 1998, *Schell* and *Linkov* 1996). The data base itself has been designed following general principles as provided, among others, by *Liebig* and *Mummenthey* (2005), *Bernhardsen* (2002), *Haines-Young* (1998) and the studies cited above. *Figure 5* represents the outline of the general data process-

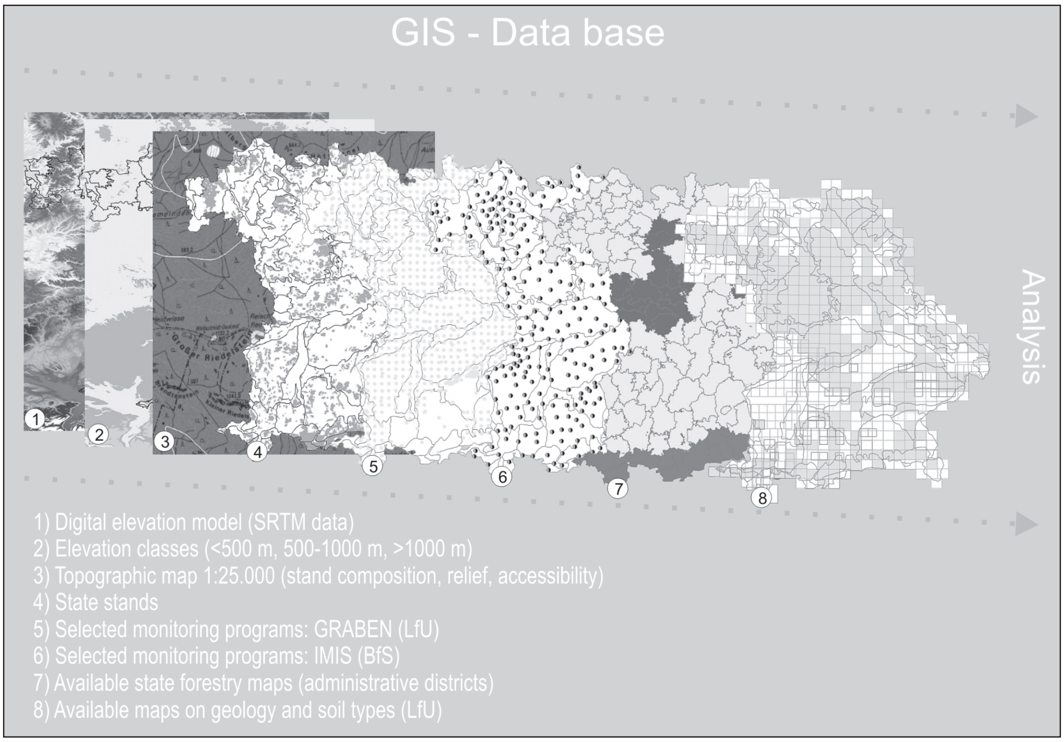


Fig. 5 Implementation of the criteria catalog via GIS interface: The GIS data base comprises all the information necessary to represent the specified criteria: (1) a digital elevation model based on SRTM satellite data is used to derive altitude information, (2) its subdivision into 3 elevation classes is used for landscape characterisation within the natural region, (3) topographic maps are introduced to determine forest stand type, terrain inclination and accessibility, (4) a shape file obtained from the Bavarian State Forestry is used to delineate state-owned forest stand areas, (5/6) coordinates of monitoring stations/sites of interest are introduced as vector data to evaluate proximities, (7/8) map margins of several maps of interest are introduced as vector data to map the availability of information on geology and soil types. The successive intersection of the various information layers, as illustrated in this figure, allows a comprehensive and feasible data analysis, filtering the most suitable and representative sites. / *Implementierung des Kriterienkatalogs innerhalb der GIS-Datenbank: Die GIS-Datenbank enthält alle wichtigen Informationen über die festgelegten Kriterien: (1) ein digitales Geländemodell auf Grundlage von SRTM Satellitendaten liefert Informationen über Relief und Höhenlagen, (2) das klassifizierte Geländemodel unterteilt die Landschaft in 3 charakteristische Höhenstufen, (3) über topographische Karten werden Bestandsart, Neigung und Zugänglichkeit der Flächen abgebildet, (4) die Kartierung von Staatsforstflächen erfolgt über ein Shapefile der Bayerischen Staatsforsten, (5/6) Lagekoordinaten sonstiger relevanter Monitoringstationen/-flächen werden als Vektordatensätze in die Datenbank eingefügt, um die Distanz zu bestehenden Netzwerken evaluieren zu können, (7/8) digitale Kartenraster im Vektorformat ermöglichen einen Überblick über die Abdeckung mit relevantem geologischen und bodenkundlichen Kartenmaterial. Die schrittweise Verschneidung der verschiedenen Informationsebenen, wie in dieser Grafik aufgezeigt, erlaubt eine umfassende und praktikable Datenanalyse zur Auswahl bestmöglich geeigneter und repräsentativer Flächen.*

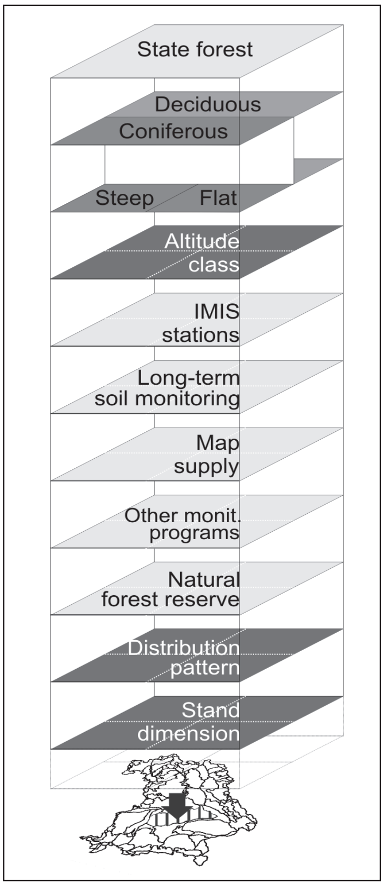


Fig. 6 Steps of site selection. – The figure schematically illustrates the selection process as applied to each natural region, starting with the selection of state forests with respect to the core criteria (stand type, slope and altitude characteristics). The following set of more pragmatic filtering criteria is eventually extended by the introduction of additional criteria concerning a distribution pattern as evenly as possible and the selection of forest stands as large as possible.
Stufen der Flächenauswahl. – Die Abbildung skizziert den für jede naturräumliche Einheit einzeln durchlaufenen Auswahlprozess, beginnend mit der Auswahl von Staatswäldern unter Berücksichtigung der genannten Kernkriterien (Bestandsart, Hangneigung, Höhenlage). Die folgende Gruppe von eher pragmatischen Filterkriterien wird abschließend erweitert um die Berücksichtigung einer möglichst gleichmäßigen Verteilung und möglichst großer Waldkomplexe.

ing. Natural regions were delineated by a shapefile obtained from the Bavarian Environment Agency (LfU). The digital elevation model for altitude classification and relief characterisation was based on NASA's free Shuttle Radar Topography Mission data (SRTM) with a 90 x 90 m spatial resolution. State forest stands were defined by an inventory shapefile obtained from the Bavarian State Forestry administration (BaySF). Stand properties, slope inclinations as well as accessibility data were taken from the digital version of the 1:25 000 or 1:50 000 topographic sheets of the Bavarian Topographical Survey. The availability of geological and soil maps was indicated by shapefile grids of the same scales (source: LfU). Coordinates for the IMIS ambient dose rate stations were provided by the Federal Office for Radiation Protection (BfS), for GRABEN and long-term soil monitoring sites by the LfU. Other Bavarian monitoring programmes on groundwater, forest climatology as well as pollutants in trees, mosses and soils were outlined in a map edited by the working group on long-term environmental monitoring (source: Bavarian State Ministry of the Environment and Public Health). Following the pre-processing of each data set, the sets were then merged with the GIS interface in order to facilitate the subsequent selection analysis (cf. *Winkelbauer* 2008).

4.1.3 Selection process

The actual selection process followed a specific order which was set in advance in order to assure the same succession of criteria for every single monitoring site (*Fig. 6*). The exclusive selection of state forest stands represents the first and major step of site selection. After that, the state forests were divided into deciduous and coniferous vegetation as well as flat and steep slope segments.

To extract representative altitudes, the DEM was grouped into three different altitude classes (< 500 m, 500-1000 m, > 1000 m) which reflect characteristic differences in humus variability (*Völkel* and *Leopold* 2006). Based on this classification, potential sites were assigned to the most frequent class. If two classes were equally abundant, both of them were covered. Because of this complex core element the analysis is significantly complicated, particularly in regions with a rugged terrain. In order to render a reliable contamination pattern, however, this step is obligatory. In addition, sites with comprehensive cartographic information and close proximity to IMIS ambient dose rate stations and stations of the long-term soil survey programmes as well as those located in natural forest reserves were preferred. Finally, site selection was revised with respect to their consistent and even distribution as well as to their position in larger contiguous stands. The remaining criteria were only additionally considered if compatible with the above-listed requirements.

4.2 Actual selection

As deduced from Section 4.1, the original default concept would in fact propose a very high number of more than 100 monitoring sites. In the context of the project, however, the number of sites had to be significantly reduced with regard to the feasibility limitations set by the Bavarian Environment Agency as the administrative office in charge of future maintenance. Thus, the concept of natural regions was ex post replaced by the alternative structure of a phytogeographical landscape classification as defined by *Wittmann* (1991) with only 15 spatial subdivisions in total. Developed in the context of forestry and land use, the later classification mainly focuses on significant changes in landscape features determining plant growth and vegetation composition. Besides relief, soil, temperature, precipitation and dryness index the parameters vegetation period and land use potential are of particular interest in this case. As such, it combines the more objective geographical natural regions (categorised by more precise geological, geomorphological and climatological differences), to bigger units of similar plant growth and land-use potential (depending on species tolerance). Unit boundaries therefore resemble each other – however on different scales. After having transferred the original sites to the new divisions, the number of sites was adjusted according to both the size of the divisions as well as the potential contamination risk with respect to a consistent distribution pattern. In the end, the number of monitoring sites was reduced to a total of 48 sites.

5. Results

5.1 Pre-selection

The original pre-selection yielded 135 sites (*Fig. 7*) throughout Bavaria, comprising either two (lowland) or four (low and high mountain) sites per natural region. The analysis of the distribution pattern shows that many monitoring sites are clustered. Certain concentration effects can also be recognised at the scale of the entire state territory. Regions of higher altitude (> 500 m), such as the Alps, are systematically covered with a higher number of monitoring sites. In combination with a subdivision into a lot of small-area natural regions, this results in an exceptionally high site density.

Concerning information supply and proximity to existing monitoring stations, the sites are generally characterised by great distances to each other, mostly exceeding 10 km and being the highest in case of the LfU long-term radionuclide soil contamination monitoring sites due to their low abundance. In con-

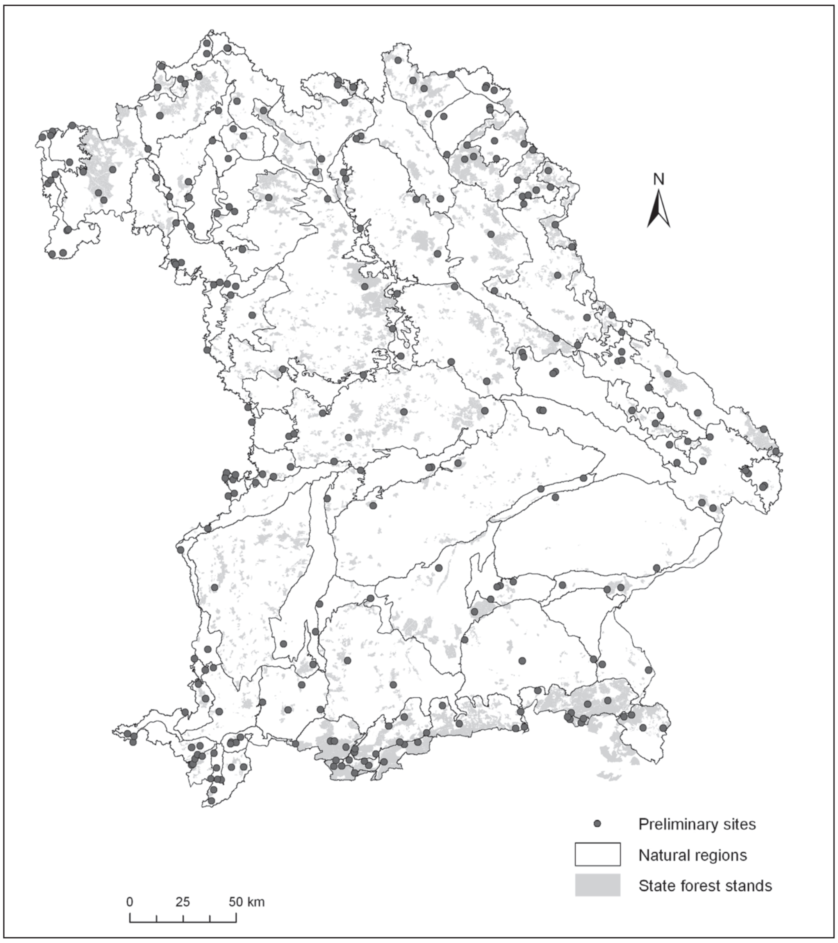


Fig. 7 Monitoring sites – Original (preliminary) selection. – The map presents the results obtained from the selection process as described in *Fig 5*. Potential monitoring sites are circled red. The fragmented distribution of state-owned forest stands, as indicated in the map (shaded grey), is the single major constraint standing in the way of the strict observance of the complex criteria system (e.g. aspect of equal distribution). / *Monitoringflächen – ursprüngliche (vorläufige) Auswahl. – In der Karte werden die Ergebnisse des in Fig. 5 beschriebenen Auswahlprozesses wiedergegeben. Die möglichen Monitoringflächen sind durch rote Punkte markiert. Die lückenhafte Verteilung von Staatswaldsflächen ist einer der Hauptgründe, die einer konsequenten Einhaltung des komplexen Kriteriensystems entgegenstehen (z.B. Ansatz der gleichmäßigen Verteilung).*

trast, as the GRABEN sites are positioned within a very closely spaced 8 x 8 km grid (*Hangen* et al. 2010), most of the sites are located within a 5 km radius to the latter. Occasional larger distances can be explained by some prominent gaps in the GRABEN grid. Furthermore, the field investigation of the sites showed that the de facto forest stand vegetation at most sites, labelled “deciduous”, either does not at all or at least only in parts match the expected properties but consists of coniferous or

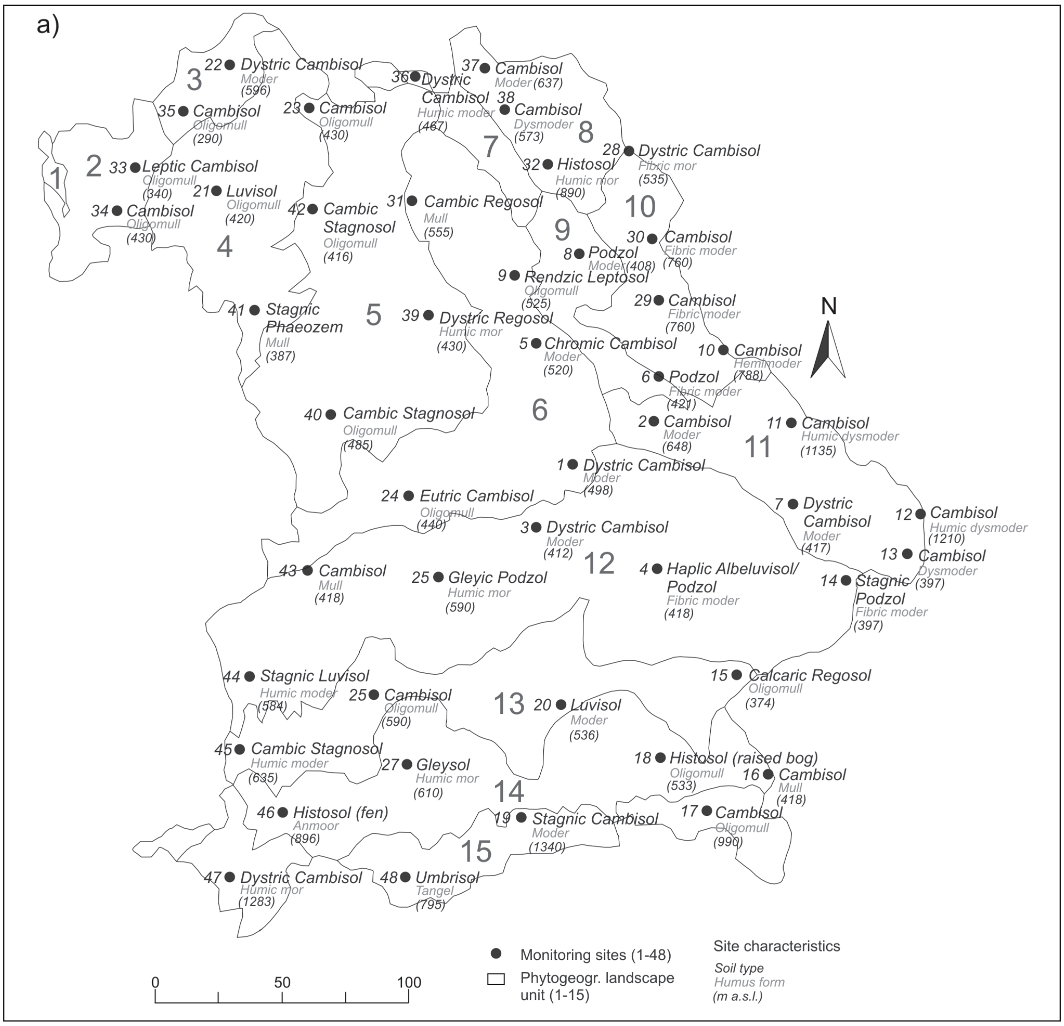
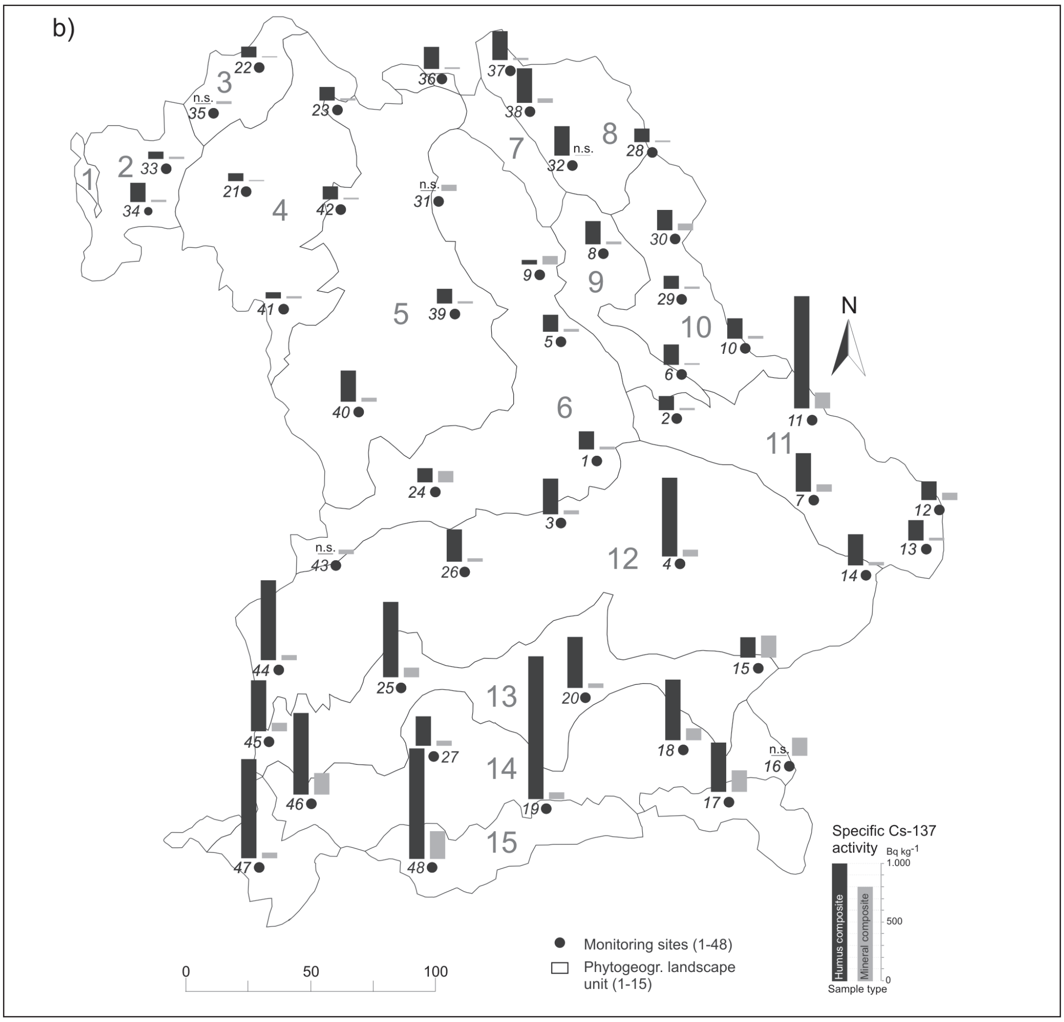


Fig. 8 Monitoring sites – Final selection (for implementation). – Presented are the final 48 monitoring sites selected after reduction by regionalisation based on the alternative regionalisation concept by phytogeographical landscape units (*Wittmann* 1991). a) Short characterisation of these sites indicating the associated soil types, humus forms and altitudes. The titles of phytogeographical landscape units (N° 1-15) are designated in *Tab. 2.* b) First investigation results on the specific Cs-137 activities in humus and mineral topsoil compartments in the first 30 cm (composite samples) by means of the official IMIS sampling standards.

Monitoringflächen – endgültige Auswahl (für Umsetzung). – Die Grafik zeigt die finalen 48 Monitoringflächen nach Reduzierung der Flächenauswahl auf Basis eines alternativen Regionalisierungskonzeptes, den standortkundlichen Landschaftseinheiten nach Wittmann (1991). a) Kurzcharakterisierung der Flächen nach Bodentyp, Humusform und Höhenlage. Die Bezeichnungen der zugehörigen standortkundlichen Landschaftseinheiten (Nr. 1-15) sind in Tab. 2 aufgeführt. b) Erste Ergebnisse zur spezifischen Cs-137-Aktivität der organischen Auflagen und des Mineralbodens innerhalb der obersten 30 cm (Mischproben) gemäß der offiziellen IMIS-Beprobungsstandards.



mixed forest instead. Reasons for such discrepancies can be both the loss of information by generalisation as well as possible out-of-date information contained in the used topographic maps. For further analysis see *Winkelbauer* (2008).

5.2 Actual monitoring sites

Figure 8a shows the final selection of 48 monitoring sites for actual implementation after reduction had been applied. As can be seen, the concentration effect of the very irregular state-owned forest stand distribution is still recognisable to a certain extent. However, the strongly clustered and thus partially redundant site distribution as caused by the original selection sketch has been successfully removed. The phytogeographical unit of the Rhein-Main river lowland (extreme northwest) has, in this version, even been completely excluded from the network because of its insignificant size and the absence of

Tab. 2 Specific ecological characteristics of the 15 phytogeographical landscape units as defined by *Wittmann* (1991). – All parameters cited according to the latter. / *Ausgewählte landschaftsökologische Parameter der 15 standortkundlichen Landschaftseinheiten nach Wittmann (1991). – Alle Parameter sind nach oben genannter Quelle (Wittmann 1991) zitiert.*

Phytogeographical landscape units		Altitude m a.s.l.		Precipitation (mm/a)	
N°	Title	Min	Max	Min	Max
1	Rhein-Main Ebene	100	150	700	750
2	Spessart-Odenwald	150	580	700	1100
3	Rhön	200	900	650	1000
4	Fränkische Platten	200	470	600	850
5	Fränk. und Schwäb. Keuper-Lias Land	230	530	650	850
6	Fränk. und Schwäb. Alb	300	620	650	1000
7	Obermain-Schollenland	270	560	650	900
8	Frankenwald, Fichtelgebirge, Vogtland	350	1050	650	1100
9	Oberpfälzer Becken- und Hügelland	350	700	650	850
10	Oberpfälzer Wald	360	900	650	1000
11	Bayerischer Wald	290	1450	700	1400
12	Tertiärhügelland, Iller-Lechplatte und Donautal	300	615	650	950
13	Schwäbisch-Bayerische Schotterplatten- und Altmoränenlandschaft	350	880	800	1400
14	Schwäbisch-Bayerische Jungmoräne und Molassevorberge	380	1050	950	1600
15	Bayerische Alpen	600	2900	1400	2500

state-owned forest stands. The intended balance of coniferous and deciduous forest areas within each unit could not be fully achieved. Yet, the absolute focus is still on the adequate representation of the typical terrain/altitude characteristics of each unit. Ranging from shallow Rego-/Leptosols to well-developed Luvisols and Podzols as well as hydromorphic Stagno-, Gleysols and peat bodies, the soils cover the whole range of representative soil types of Bavaria. Reflecting its dominance as the most prominent soil type within the study region, the majority of sites is represented by Cambisols, most of which are specified as Dystric Cambisols. Most frequently, the soils are covered by moder or mull humus forms. As progressing acidification is a common phenomenon in many Bavarian forest ecosystems, some of the sites show pronounced initial podsolic tendencies.

So far, all 48 sites have been installed and sampled comprising an actual inventory of 1 soil profile (1 m depth), 2 soil monoliths (30 cm depth), and 2 composite samples (30 cm depth) for each site, which altogether render more than 880 gammaspectrometric records on the specific activity of Cs-137. The composite samples represent the official AVV-IMIS standard procedure for Cs-137 monitoring in soil according to Bundesministerium für Justiz (2006). Both soil profiles and monoliths form the basis for a horizon specific sampling procedure as recommended by *Völkel* and *Leopold* (2006). Beside gammaspectrometry, these samples have also undergone supplementary lab analysis including total C- and N contents, pH and effective cation exchange capacity as well as grain size analysis of mineral soil samples.

5.3 General Cs-137 contamination in Bavaria

Figure 8b illustrates the results of the official AVV-IMIS sampling procedure according to Bundesministerium für Justiz (2006). Representing the average specific Cs-137 mass activity in Bq kg^{-1}, the results allow a first glance on the current contamination situation in Bavaria.

The procedure was to extract 30 random single samples from across the entire site area, cut out by a 30 cm long metal tube (Ø 5.5 cm). The sample matter in the tubes was then carefully separated into a) humus (excluding L horizons) and b) mineral horizons. For each category the sample matter of all 30 extractions per site was then assembled to one specific composite sample (humus, mineral). For all 48 sites, this corresponds to a total of 1440 cut-ins and 96 composite samples. At the sites RF16, RF31 and RF43 – all mull (L, Ah) dominated profiles – however, humus records are missing due to systematic reasons, as no such samples could be produced according to IMIS standards (no L sampling!). The same applies to the site RF35 where not enough sampling material could be provided (shallow oligomull humus). Also, no mineral record is available from site RF32, as this is a histosol on solid bedrock.

Regarding the uppermost ~ 30 cm of the soil, the average specific Cs-137 mass activity recorded varies from 31.78 to 1214.00 Bq kg^{-1} (Ø 313.38 Bq kg^{-1}) in the humus sections and from 5.68 to 232.00 Bq kg^{-1} (Ø 51.13 Bq kg^{-1}) in the mineral sections, demonstrating significant spatial variations throughout the entire study region. Highest activities are found to occur in the high and low mountain regions of the Alps and the Bavarian forest highlands, whereas sites in the northwestern parts are generally characterised by strikingly low contamination levels. Yet, despite basic spatial variations, the results highlight a general common phenomenon: specific Cs-137 activities in humus samples are on average almost ten times (9.21) higher than in mineral samples. Only the records of the sites RF9, RF15 and RF35 show opposite results, i.e. the contamination in the mineral soil exceeds the humus contamination. Detailed analysis on the horizon based profile and monolith samples is currently running. For further data see *Völkel* et al. (2009).

6. Discussion

6.1 Monitoring sites

The orientation of sites along a grid is certainly very reasonable for various reasons, such as an unbiased sampling design and the elimination of large sampling gaps (*Hangen* et al. 2010, Bundesministerium für Justiz 2006, *Wang* and *Qi* 1998, *Nießl* et al. 1996, *Borgman* and *Quimby* 1988). Nevertheless, grid patterns bear the disadvantage of a random sampling without any ecological reference and differentiation (*Völkel* and *Leopold* 2006, *Mercat-Rommens* and *Renaud* 2005, *Dubois* et al. 2004, *Bossew* 2003, *Howard* 2000). Our approach has specifically been developed to overcome this deficiency, replacing a neutral grid pattern by a selective and systematic site distribution pattern representing the various ecological landscapes within the study area. Such an approach renders a completely different distribution pattern. Gaps frequently occur at both approaches (pre-selection, actual selection), mainly however as a logical consequence of the uneven distribution and sparse occurrence of state-forest stands (*Fig. 1b*), as only 30 % of the Bavarian territory are actually forest-covered.

The limitation is even more aggravated by the additional site demands of a specific vegetation, inclination and altitude classes respectively. As the necessary combination of the various criteria much reduces the availability of suitable areas, it should be discussed to ease some of the restrictions. Easing, for instance, the strict but merely pragmatic restriction to state-forest stands by also allowing the location of sites in private forests would help, in particular in those units where there are no or only very few state-owned forest stands (*Tab. 1*). The approach chosen depends on the monitoring objective, though. If the focus of the monitoring is not supposed to be on the Bavarian ecosystem in general, but on the governmental forest production only, the placing of sites on state-forest land only is justified. The requirement of equal areas of both deciduous and coniferous stands should also be discussed, which only makes sense as long as both types are equally represented within a given landscape unit. In case of a significantly smaller share of deciduous forests, the exclusive monitoring of coniferous sites is likely to deliver more meaningful results, in particular as coniferous forests are prone to higher contamination risks. As a third example, the location of monitoring sites in both low and high mountain regions makes sense, with regard to higher primary depositions (*Renaud* et al. 2003, *de Cort* et al. 1998) and to generally higher humus and Cs-137 variability (*Völkel* and *Leopold* 2006) with increasing altitudes. However, the call for four sites in each region highly increases the workload, making any routine sampling problematic or even unfeasible.

Effective reduction of the workload and declustering can be achieved by merging several small units of very similar landscape characteristics as practiced in the course of our own site selection procedure. Although the concept proposed by *Wittmann* (1991) suffers from some generalisation, mostly at the expense of substrate characteristics, it is, however, a useful compromise in terms of administrative feasibility. Due to the generally high spatial complexity of soil and humus types as well as of other small scale effects (e.g. exposition), it is debatable whether the concept of natural regions would deliver an effectively higher accuracy at all. Hence, since the range of precipitation variability (i.e. one of the most important parameters) is quite similarly represented in both approaches (*Tabs. 1* and *2*), the reduction of information detail is assumed to be acceptable.

The GIS data base is a very valuable tool for the implementation of the site selection process. With regard to optimised and thus faster analysis, however, some modifications are recommended. Thus it would be an improvement if the general availability of geological, soil and forestry maps would not only be registered, but their content be included as vector data (*de Nooijer* and *Chabanyuk* 2002, *Deville-Cavelin* et al. 2002, *Kolejka* 2002a), facilitating the automatic intersection with other spatial information as well as their integration into interpolation and modelling. This would not be an option, though, for a study encompassing such a large area as the present one, as official digital vector maps do not yet cover the whole region, and as the data are quite expensive. Another major problem to overcome is the determination of stand composition. Detailed stand information of the Bavarian State Forestry is currently transferred to a comprehensive digital inventory. The alternative use of airborne data as e.g. proposed by *Siegel* and *Palko* (2002) is a matter of cost, memory capacity and processing power. Until the completion of the forestry inventory, working with topographic raster maps despite several uncertainties is therefore nonetheless a viable approach, which at least significantly reduces the data load.

6.2 General Cs-137 contamination in Bavaria

The presented results on the regional distribution characteristics of Cs-137 in Bavarian forest soils are in good agreement with previous findings, underlining a certain influence of organic layers on the Cs-137 retention in forest soils and ecosystems (cf., among others, *Konopleva* et al. 2009, *Zhiyanski* et al. 2008, *Völkel* and *Leopold* 2006, *Kruse-Irmer* and *Giani* 2003, *Kruyts* and *Delvaux* 2002). The fact that even 25 years after the Chernobyl accident organic layers are still characterised by comparatively high mass activities substantiates the assumption that there is only minor vertical translocation of Cs-137 throughout forest soil profiles in general. Yet, it has to be considered that IMIS composite samples only render information on the relative Cs-137 mass activity per kg humus or mineral soil. In order to facilitate a detailed resolution of the vertical distribution of Cs-137 within a soil profile, the analysis has to account for differences in horizon bulk densities and thicknesses in some way by transferring relative mass activities (Bq kg^{-1}) to effective areal activities (Bq m^{-2}). Therefore, the project framework also schedules gamma spectrometric records on horizon-based samples for each site to render both horizon-specific as well as total areal Cs-137 activities. Comprehensive analysis on the latter is in progress. In addition, the specific reasons for a possible translocation retardation have to be further investigated. Restrained litter decomposition and turn-over in forest ecosystems is certainly one of the main reasons (*Zhiyanski* et al. 2008) besides the preferential integration of highly bioavailable Cs-137 into the matter cycle significantly depending on humus properties such as the abundance of incompletely decomposed conversion products (*Kruyts* and *Delvaux* 2002) and/or myccorhizal fungi (*Steiner* et al. 2002, *Brückmann* and *Wolters* 1994) as well as ammonium concentrations (*Konopleva* et al. 2009). The occurrence of spatial interrelations, as highlighted by the present study (*Fig. 8b*), also supports these assumptions. The influence of (phyto-)geographical factors (increased annual rainfall, reduced metabolic soil biota activity, restrained decomposition) on regions of high Cs-137 magnitudes, as mentioned above, is obvious (see Introduction). Yet, higher contamination in most high-altitude regions is to a certain extent also linked to high-precipitation events and thus very effective radionuclide wash-out at the time of deposition (cf. *Bayer* et al. 1996). A definite differentiation and quantification of these two effects ex post, without clear reference data of the year 1986, is very complex and beyond the scope of this paper, though.

7. Conclusion and Future Prospects

Forest ecosystems are hot spots of long-term Cs-137 contamination. To reduce possible negative effects to biosphere and mankind, comprehensive monitoring has to be conducted, considering the exceptional role of organic layers. The standardised default guideline by *Völkel* and *Leopold* (2006) systemises the most important factors of humus composition and can be transferred to any forest environment worldwide. Selecting the most representative monitoring sites for the various landscape units is a sound concept based on the principles of radioecology. Long-term monitoring concepts, however, have to achieve the difficult balance between scientific demands of a high level of detail versus feasibility. Hence, practical limitations, such as the number of monitoring sites, are inevitable. A coherent reduction, as undertaken in the present study, will also yield meaningful and valid results. Despite the significant reduction to a final number of 48 monitoring sites, the monitoring succeeds in presenting a very comprehensive picture of the broad range of distinctively varying Cs-137 activities throughout the Bavarian forests. Comprising a total of more than 880 gammaspectrometric records, the study provides a comprehensive inventory and as such a unique update on the Cs-137 contamination in Bavarian forest soils. The results highlight characteristic spatial patterns and prove the exceptional role of humus for Cs-137 retention and potential bioavailability, as claimed in previous studies. Regarding the technical implementation of the new concept, the use of a GIS interface has proven to be a very helpful methodological tool. The data set allows fast information retrieval and offers the possibility of further studies via geostatistics as well as process modelling.

As a next step, particularly the horizon-specific gamma spectrometric records will be used to examine these spatial patterns of Cs-137 distribution in Bavarian forest ecosystems with particular respect to the influence of site-specific ecological and edaphic parameters. These records also allow supplementary analysis on the effective amount of bioavailable Cs-137 (e.g. RIP radiocesium interception potential of a soil, concentration of exchangeable Cs-137 in soil solution, K^+/NH_4^+ concentrations etc.) in case of continuative questions on soil-to-plant transfer risks (cf. amongst others *Konopleva* et al. 2009). Hence, the established data base provides a unique and vast basis to further investigate and quantify the driving factors of the vertical distribution of Cs-137 activities in forest soils and to comprehensively assess the long-term recovery behaviour of different forest environments in Bavaria.

8. References

Ad-hoc-AG Boden (Hrsg.) 2005: Bodenkundliche Kartieranleitung. – 5. Auflage. – Stuttgart, Hannover

Andolina, J. and *O. Guillitte* 1990: Radiocesium Availability and Retention Sites in Forest Humus. – In: *Desmet, G., P. Nassimbeni* and *M. Belli* (eds.): Transfer of Radionuclides in Natural and Semi-Natural Environments. – London et al.: 135-143

Bastian, O. (Hrsg.) 1999: Analyse und ökologische Bewertung der Landschaft. – Heidelberg

Bayer, A., E. Wirth, R. Haubelt, K. König, E. Ettenhuber, I. Winkelmann und *H. Rühle* 1996: Kontamination und Strahlenexposition in Deutschland nach dem Unfall im Kernkraftwerk Tschernobyl. – In: *Bayer, A., A. Kaul* und *C. Reiners* (Hrsg.): Zehn Jahre nach Tschernobyl: eine Bilanz. Seminar des Bundesamtes für Strahlenschutz und der Strahlenschutzkommission, München. – Stuttgart et al.: 127-152

Bayerische Landesanstalt für Wald und Forstwirtschaft (Hrsg.) 2004: Erfolgreich mit der Natur. Ergebnisse der zweiten Bundeswaldinventur in Bayern. – Freising. – Online available at: http://www.lwf.bayern.de/veroeffentlichungen/lwf-spezial/02/lwf-spezial_02.pdf, 14/04/2011

Bayerisches Landesamt für Umwelt 2006a: Bericht über die Veränderungen der Radioaktivität in Böden seit dem Reaktorunfall von Tschernobyl vor 20 Jahren. Eine Bestandsaufnahme der seitdem in Bayern durchgeführten Untersuchungen. – Augsburg. – Online available at: http://www.lfu.bayern.de/strahlung/tschernobyl/doc/bodenschutzbericht_2006.pdf, 25/09/2007

Bayerisches Landesamt für Umwelt 2006b: Tschernobyl – Bayern 20 Jahre danach. – Augsburg. – Online available at: http://www.lfu.bayern.de/strahlung/tschernobyl/doc/tschernobyl.pdf, 25/09/2007

Bernhardsen, T. 2002: Geographic Information Systems: An Introduction. – New York

Borgman, L.E. and *W.F. Quimby* 1988: Sampling for Tests of Hypothesis when Data are Correlated in Space and Time. – In: *Keith, L.H.* (ed.): Principles of Environmental Sampling. – Washington D.C.: 25-43

Bossew, P. 2003: Radiological Mapping: Chernobyl Experiences in Austria and Emergency Response. – In: *Dubois, G., J. Malczewski* and *M. de Cort* (eds.): Mapping Radioactivity in the Environment: Spatial Interpolation Comparison 1997. – Luxembourg: 3-20

Brückmann, A. and *V. Wolters* 1994: Microbial Immobilization and Recycling of ^{137}Cs in the Organic Layers of Forest Ecosystems: Relationship to Environmental Conditions, Humification and Invertebrate Activity. – Science of the Total Environment. Special Issue: Forests and Radioactivity **157**: 249-256

Bundesministerium für Justiz 2006: Allgemeine Verwaltungsvorschrift zum integrierten Mess- und Informationssystem zur Überwachung der

Radioaktivität in der Umwelt (IMIS) nach dem Strahlenschutzvorsorgegesetz (AVV-IMIS) vom 13. Dezember 2006. – Bundesanzeiger **244**a

Comans, R.N.J., M. Haller and *P. de Preter* 1991: Sorption of Cesium on Illite: Non-equilibrium Behaviour and Reversibility. – Geochimica et Cosmochimica Acta **55** (2): 433-440

Cremers, A., A. Elsen, P. de Preter and *A. Maes* 1988: Quantitative Analysis of Radiocaesium Retention in Soils. – Nature **335**: 247-249

de Cort, M., G. Dubois, S.D. Fridman, M.G. Germenchuk, Y.A. Izrael, A. Janssens, A.R. Jones, G.N. Kelly, E.V. Kvasnikova, I.I. Matveenko, I.M. Nazarov, Y.M. Pokumeiko, V.A. Sitak, E.D. Stukin, L.Y. Tabachny, Y.S. Tsaturov and *S.I. Avdyushin* 1998: Atlas of Caesium Deposition on Europe after the Chernobyl Accident. – Luxembourg. – Online available at: http://rem.jrc.ec.europa.eu/RemWeb/pastprojects/atlasfiles/TEXT/ENGLISH.PDF, 13/02/2007

de Koning, A., A.V. Konoplev and *R.N.J. Comans* 2007: Measuring the Specific Caesium Sorption Capacity of Soils, Sediments and Clay Minerals. – Applied Geochemistry **22** (1): 219-229

de Nooijer, P.G. and *V. Chabanyuk* 2002: Providing Information in Relation to Chernobyl and the Role of GIS. – In: *Kolejka, J.* (ed.): Role of GIS in Lifting the Cloud off Chernobyl. – NATO Science Series: IV, Earth and Environmental Sciences **10**. – Dordrecht: 25-48

Deville-Cavelin, G., H. Biesold, C. Brun-Yaba and *V. Chabanyuk* 2002: The Consequences of the Chernobyl Accident: First Results in the Radioecology Project of the French-German Initiative. – In: *Kolejka, J.* (ed.): Role of GIS in Lifting the Cloud off Chernobyl. – NATO Science Series: IV, Earth and Environmental Sciences **10**. – Dordrecht: 49-66

Dowdall, M., W. Standring, G. Shaw and *P. Strand* 2008: Will Global Warming Affect Soil-to-Plant Transfer of Radionuclides? – Journal of Environmental Radioactivity **99** (11): 1736-1745

Dubois, G., T. Tollefsen, P. Bossew and *M. de Cort* 2004: GIS and Radioecology: A Data Perspective. – 10th EC GI & GIS Workshop, ESDI State of the Art, Warsaw, Poland, 23-25 June 2004. – Online available at: http://www.ec-gis.org/Workshops/10ec-gis/papers/24june_dubois.pdf, 17/04/2007

Fielitz-Vogl, U. 1992: Ausbreitung und Transfer von Radiocäsium entlang des Pfades Boden-Pflanze-Reh in zwei unterschiedlichen Waldökosystemen. – Dissertation. – Göttingen

Haines-Young, R.H. 1998: Landscape Ecology and GIS. – London.

Hangen, E., W. Olbricht and *M. Joneck* 2010: Regionalization of Organic Pollutants in Bavarian Soils: The Performance of Indicator Kriging. – Journal of Plant Nutrition and Soil Science **173** (4): 517-524

Hird, A.B., D.L. Rimmer and *F.R. Livens* 1996: Factors Affecting the Sorption and Fixation of Caesium in Acid Organic Soil. – European Journal of Soil Science **47** (1): 97-104

Hohmann, U. and *D. Huckschlag* 2005: Investigations on the Radiocaesium Contamination of Wild Boar (Sus Scrofa) Meat in Rhineland-Palatinate: A Stomach Content Analysis. – European Journal of Wildlife Research **51**: 263-270

Howard, B.J. 2000: The Concept of Radioecological Sensitivity. – Radiation Protection Dosimetry **92** (1-3): 29-34

Kammerer, L., L. Hiersche and *E. Wirth* 1994: Uptake of Radiocaesium by Different Species of Mushrooms. – Journal of Environmental Radioactivity **23** (2): 135-150

Kiefer, P., G. Pröhl, H. Müller, G. Lindner, J. Drissner and *G. Zibold* 1996: Factors Affecting the Transfer of Radiocaesium from Soil to Roe Deer in Forest Ecosystems of Southern Germany. – Science of the Total Environment **192** (1): 49-61

Kolejka, J. 2002a: Editor's Preface. – In: *Kolejka, J.* (ed.): Role of GIS in Lifting the Cloud off Chernobyl. – NATO Science Series: IV, Earth and Environmental Sciences **10**. – Dordrecht: unpaged

Kolejka, J. (ed.) 2002b: Role of GIS in Lifting the Cloud off Chernobyl. – NATO Science Series: IV, Earth and Environmental Sciences **10**. – Dordrecht

Konopleva, I., E. Klemt, A. Konoplev and *G. Zibold* 2009: Migration and Bioavailability of ^{137}Cs in Forest Soil of Southern Germany. – Journal of Environmental Radioactivity **100** (4): 315-321

Kruse-Irmer, S. and *L. Giani* 2003: Vertical Distribution and Bioavailability of ^{137}Cs in Organic and Mineral Soils. – Journal of Plant Nutrition and Soil Science **166** (5): 635-641

Kruyts, N. and *B. Delvaux* 2002: Soil Organic Horizons as a Major Source for Radiocesium Biorecycling in Forest Ecosystems. – Journal of Environmental Radioactivity **58** (2-3): 175-190

Kruyts, N., Y. Thiry and *B. Delvaux* 2000: Respective Horizon Contributions to Cesium-137 Soil-to-Plant Transfer: A Rhizospheric Experimental Approach. – Journal of Environmental Quality **29** (4): 1180-1185

Liebig, W. und *R.D. Mummenthey* 2005: ArcGIS – ArcVIEW 9. – Norden

Maes, E., A. Iserentant, J. Herbauts and *B. Delvaux* 1999: Influence of the Nature of Clay Minerals on the Fixation of Radiocaesium Traces in an Acid Brown Earth-Podzol Weathering Sequence. – European Journal of Soil Science **50** (1): 117-125

Mercat-Rommens, C. and *P. Renaud* 2005: From Field Studies to Risk Management: The SENSIB Project. – Radioprotection **40** (1): 785-790

Meynen, E., J. Schmithüsen, J. Gellert, E. Neef, H. Müller-Miny und *H.J. Schultze* (Hrsg.) 1962: Handbuch der naturräumlichen Gliederung Deutschlands. – Bad Godesberg

Nießl, A., K. Goussios und *H. Stein* 1996: Überwachung der Radioaktivität in der Umwelt. – In: Bayerisches Landesamt für Umweltschutz (Hrsg.): 25 Jahre LfU. Tätigkeitsbericht 1995. – Schriftenreihe des Bayerischen Landesamtes für Umweltschutz **137**: 212-215

Pietrzak-Flis, Z., I. Radwan, L. Rosiak and *E. Wirth* 1996: Migration of ^{137}Cs in Soils and its Transfer to Mushrooms and Vascular Plants in Mixed Forest. – Science of the Total Environment **186** (3): 243-250

Putyrskaya, V., E. Klemt, H. Paliachenka and *G. Zibold* 2003: ^{137}Cs Accumulation in *Elaphomyces granulatus fr.* and its Transfer to Wild Boar. – In: *Mitchell, N., V. Licina* and *G. Zibold* (eds.): Proceedings of the 13th Annual Meeting of ESNA. Working Group 3: Soil-Plant-Relationships. – Online available at: http://opus.bsz-bw.de/hsbwgt/volltexte/2005/4/pdf/WG3Viterbo03.pdf, 30/03/2007: 1-5

Renaud, P., L. Pourcelot, J.-M. Métivier and *M. Morello* 2003: Mapping of ^{137}Cs Deposition over Eastern France 16 Years after the Chernobyl Accident. – Science of the Total Environment **309** (1): 257-264

Rühm, W., M. Steiner, L. Kammerer, L. Hiersche and *E. Wirth* 1998: Estimating Future Radiocaesium Contamination of Fungi on the Basis of Behaviour Patterns Derived from Past Instances of Contamination. – Journal of Environmental Radioactivity **39** (2): 129-147

Schaller, G., C. Leising, R. Krestel und *E. Wirth* 1993: Vergleichende Betrachtung von Cäsium und Kalium im Boden. – Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit. – Schriftenreihe Reaktorsicherheit und Strahlenschutz **370**. – Eggenstein-Leopoldshafen

Schell, W.R. and *I. Linkov* 1996: A Modeling Approach to Remediation of Forests Contaminated by Radionuclides. – In: *Luykx, F.F.* and *M.J. Frissel* (eds.): Radioecology and the Restoration of Radioactive-Contaminated Sites. – NATO ASI Series: Partnership Sub-Series 2. Environment **13**. – Dordrecht: 115-136

Schilling, B., J. Hammerl, G. Holzner, C. Mahler und *G. Stimmelmeier* 2005: Monitoring der Radioaktivität im Boden: Veränderungen zwischen 1990 und 2003. – GLA Fachberichte **23**. – München: 1-54

Shaw, G. and *J.N.B. Bell* 1994: Plants and Radionuclides. – In: *Farago, M.E.* (ed.): Plants and the Chemical Elements: Biochemistry, Uptake, Tolerance and Toxicity. – Weinheim: 179-220

Shcheglov, A.I., O.B. Tsvetnova and *A.L. Klyashtorin* 2001: Biogeochemical Migration of Technogenic Radionuclides in Forest Ecosystems: By the Materials of a Multiyear Study in the Areas Severely Contaminated due to the Chernobyl Accident. – Moscow

Siegel, C. and *S. Palko* 2002: Situation Assessment for Mitigation Activities: Tools for Building Geographic Knowledge: From Geodata to Geoinformation to Geoknowledge? – In: *Kolejka, J.* (ed.): Role of GIS in Lifting the Cloud off Chernobyl. – NATO Science Series: IV, Earth and Environmental Sciences **10**. Dordrecht: 1-12

Steiner, M., I. Linkov and *S. Yoshida* 2002: The Role of Fungi in the Transfer and Cycling of Radionuclides in Forest Ecosystems. – Journal of Environmental Radioactivity **58** (2-3): 217-241

Stemmer, M., A. Hromatka, H. Lettner and *F. Strebl* 2005: Radiocesium Storage in Soil Microbial Biomass of Undisturbed Alpine Meadow Soils and its Relation to ^{137}Cs Soil-Plant Transfer. – Journal of Environmental Radioactivity **79** (2): 107-118

Sweeck, L., J. Wauters, E. Valcke and *A. Cremers* 1990: The Specific Interception Potential of Soils for Radiocaesium. – In: *Desmet, G., P. Nassimbeni* and *M. Belli* (eds.): Transfer of Radionuclides in Natural and Semi-Natural Environments. – Barking: 249-258

van Voris, P., C. Cowan, D.A. Cataldo, R.E. Wildung and *H.H. Shugart* 1990: Chernobyl Case Study: Modeling the Dynamics of Long-Term Cycling and Storage of ^{137}Cs in Forested Ecosystems. – In: *Desmet, G., P. Nassimbeni* and *M. Belli* (eds.): Transfer of Radionuclides in Natural and Semi-Natural Environments. – Barking: 61-74

Völkel, J. 1995: Zur Erfassung der räumlichen Verteilung von Radiocäsium des Tschernobyl-Fallouts in Waldböden. – In: Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (Hrsg.): 9. Fachgespräch zur Überwachung der Umweltradioaktivität, München-Neuherberg, 25.-27.4.1995. – Bonn: 218-223

Völkel, J. 1998: Tschernobyl-Cäsium in Böden von Stadt- und Waldökosystemen. – In: *Frühauf, M.* und *U. Hardenbicker* (Hrsg.): Geowissenschaftliche Umweltforschung im Mitteldeutschen Raum. – Sammelband der 3. Tagung zur Geographischen Umweltforschung in Mitteldeutschland im Rahmen der Universitätspartnerschaft Halle-Jena-Leipzig an der Martin-Luther-Universität Halle-Wittenberg, 6.-7. November 1997. – Universitätszentrum für Umweltwissenschaften, Schriftenreihe N.F. **2**. – Halle: 191-197

Völkel, J. 2002: Bioverfügbarkeit von Radiocäsium in unterschiedlichen naturräumlichen Einheiten Bayerns. – Regensburger Beiträge zur Bodenkunde, Landschaftsökologie und Quartärforschung **1**. – Regensburg. – Online available at: https://mediatum2. ub.tum.de/node?id=634400, 03/07/2006

Völkel, J., K. Hürkamp, M. Leopold und *J. Winkelbauer* 2009: Monitoring zur Standortvariabilität von Radiocäsium in Böden. Abschlussbericht. – Beiträge zur Bodenkunde, Landschaftsökologie und Quartärforschung (BOLAQ) **15**. – Freising. – Online available at: http://mediatum2.ub.tum.de/node?id= 982527, 12/07/2010

Völkel, J. und *M. Leopold* 2006: Standortvariabilität von Radiocäsium in Böden. – Regensburger Beiträge zur Bodenkunde, Landschaftsökologie und Quartärforschung (BOLAQ) **10**. – Regensburg. – Online available at: http://mediatum2.ub.tum.de/node?id =634399, 30/08/2006

Wang, X.J. and *F. Qi* 1998: The Effects of Sampling Design on Spatial Structure Analysis of Contaminated Soil. – Science of the Total Environment **224** (1): 29-41

Winkelbauer, J. 2008: Monitoringflächen in Waldökosystemen Bayerns zur Überwachung anthropogen induzierter Radionuklid-Aktivitäten am Beispiel von Radiocäsium: GIS-gestützte Konzeptionierung und deren Umsetzung anhand zweier Praxisbeispiele. – Beiträge zur Bodenkunde, Landschaftsökologie und Quartärforschung (BOLAQ) **14**. – Freising. – Online available at: https://mediatum2.ub.tum.de/node?id=982563, 06/07/2010

Wittmann, O. 1991: Standortkundliche Landschaftsgliederung von Bayern. Übersichtskarte 1:1000000 und Abhängigkeitsbeziehungen der Bodennutzung. – GLA-Fachberichte **5**. – München

Zhiyanski, M., J. Bech, M. Sokolovska, E. Lucot, J. Bech and *P.-M. Badot* 2008: Cs-137 Distribution in Forest Floor and Surface Soil Layers from Two Mountainous Regions in Bulgaria. – Journal of Geochemical Exploration **96** (2-3): 256-266

Summary: A Novel Approach to Monitoring the Cs-137 Contamination of Forest Soils in Bavaria, Germany

Latest incidents in Japan prove that nuclear accidents are still a hazardous threat to ecosystems worldwide. Regarding the radioactive fission product Cs-137, particularly forest soils are hot spots of long-term contamination. In the case of forest-rich Bavaria, one of the German states affected most severely by Chernobyl-born radionuclide deposition in 1986, this topic is of high relevance. Particular considerations also include the development of specific monitoring approaches to effectively determine and evaluate the distribution of Cs-137 in forests. Numerous previous studies have indicated that monitoring should take special account of the role of humus for Cs-137 mobility and bioavailability in this context. Official programmes in Bavaria, however, lack such considerations concerning the controlling influence of humus. Hence, a new monitoring project has been established across the Bavarian state forests, together with the Bavarian State Ministry of the Environment and Public Health, focussing on humus-controlling landscape parameters as crucial core criteria. The concept design divides state forests into several units of distinctive landscape types and subjects each of them to a strict filtering scheme in order to create a consistent selection of deciduous/coniferous as well as steep/flat monitoring sites in representative altitudes. Site area varies with altitude (low/high mountains: 30 x 30 m; lowlands: 50 x 50 m). Additional filters further consider site homogeneity, proximity to other official monitoring instruments, information supply, turbation, accessibility and regular distribution. This paper explains the transfer of these standards into a GIS-based application routine and discusses its feasibility. Besides, the established monitoring sites and first results on current Cs-137 loads are presented. In summary, a total of 48 monitoring sites were established (48 soil profiles, 96 soil monoliths, 96 composite samples). The GIS interface proved to be a helpful tool in this context. The presented monitoring succeeds in providing a comprehensive picture of the broad range of Cs-137 activities throughout Bavarian forest soils. Composite samples, taken according to official AVV-IMIS standards (~ 30 random samples per site conjoined to one humus and mineral composite each), show that the average specific Cs-137 activity within the uppermost ~ 30 cm varies between 31.78-1214.00 Bq kg^{-1} (humus) and 5.68-232.00 Bq kg^{-1} (mineral soil). The results highlight characteristic spatial patterns and demonstrate that the specific Cs-137 activity in humus is still comparatively high. In all, the established data base provides a solid basis for further investigations on the driving factors of the vertical Cs-137 distribution in forest soils as well as on questions of bioavailability and effective soil-to-plant transfer. Beyond that, the presented approach can as well be transferred to any other forest soil contaminant of interest.

Zusammenfassung: Neuer Ansatz zur Überwachung der Cs-137-Belastung von Waldböden in Bayern, Deutschland

Die aktuellen Vorfälle in Japan verdeutlichen eindrücklich, dass nukleare Unfälle nach wie vor eine gefährliche Bedrohung für Ökosysteme weltweit darstellen. Das radioaktive Spaltprodukt Cs-137 sorgt insbesondere in Waldböden für lang anhaltende Kontaminations-Hotspots. Für Bayern ist diese Problematik aufgrund des Waldreichtums und der extrem hohen Radionuklidbelastung infolge des Reaktorunfalls von Tschernobyl 1986 von äußerst hoher Relevanz. Das betrifft auch die Entwicklung gezielter Monitoringansätze, um die Verteilung von Cs-137 in Wäldern effektiv erfassen und zukünftige Schutzmaßnahmen verbessern zu können. Zahlreiche aktuelle Studien weisen darauf hin, dass dem Einfluss der organischen Auflagen auf die Mobilität und Bioverfügbarkeit von Cs-137 dabei verstärkt Rechnung getragen werden muss. Da offizielle Monitoringprogramme in Bayern diesen Zusammenhang bisher kaum berücksichtigen, wurde in Zusammenarbeit mit dem Bayerischen Staatsministerium für Umwelt und Gesundheit ein völlig neues Monitoringkonzept erstellt. In dessen Fokus stehen als zentrale Auswahlkriterien vor allem landschaftsökologische Parameter mit besonderem Einfluss auf die Humusbildung. Anhand des Konzepts werden die Staatswälder unterteilt nach Standortkundlichen Landschaftseinheiten. Jede dieser Einheiten durchläuft anschließend ein spezielles Auswahlschema mit dem Ziel einer ausgewogenen Berücksichtigung von Nadel- und Laubwäldern, steilen und flachen Geländepositionen sowie repräsentativen Höhenstufen. Die Flächengröße richtet sich nach der jeweiligen Höhenlage (Mittel-/Hochgebirge: 30 x 30 m; Flachland: 50 x 50 m). Als weitere Kriterien werden Flächenhomogenität, Nähe zu sonstigen offiziellen Monitoringprogrammen, Informationslage zu Standorten, Turbationsereignisse, Erreichbarkeit und eine gleichmäßige Verteilung berücksichtigt. Im Rahmen dieser Arbeit wird die GIS-basierte Umsetzung dieses Auswahlprozesses dargestellt und diskutiert. Darüber hinaus werden die ausgewählten Monitoringflächen inklusive erster Ergebnisse bezüglich aktueller Cs-137-Aktivitäten in den Böden präsentiert. Anhand des Auswahlprozesses wurden insgesamt 48 Flächen ausgewählt (48 Bodenprofile, 96 Bodenmonolithen, 96 Mischproben). Der GIS-basierte Ansatz hat sich dabei als hilfreiche Methode bewährt. Die nach offiziellen AVV-IMIS Standards erhobenen Mischproben (je eine Mischprobe für organische Auflagen bzw. für Mineralboden aus ~ 30 zufällig verteilten Sondierungen pro Fläche) ergeben, dass die durchschnittliche spezifische Cs-137-Aktivität innerhalb der obersten ~ 30 cm zwischen 31,78-1214,00 Bq kg^{-1} (organische Auflagen) und 5,68-232,00 Bq kg^{-1} (Mineralboden) schwankt. Die Ergebnisse heben charakteristische räumliche Verteilungsmuster hervor und verdeutlichen die nach wie vor sehr hohen Cs-137-Aktivitäten in den organischen Auflagen. Darüber hinaus liefert das umfangreiche Dateninventar eine fundierte Basis für zukünftige Fragestellungen und Untersuchungen bezüglich der steuernden Faktoren der vertikalen Verteilung von Cs-137 und seiner Bioverfügbarkeit (Transfer Boden-Pflanze) in Waldböden allgemein. Ebenso kann der vorgestellte Ansatz universell auf andere Schadstoffe in Waldböden übertragen werden.

Résumé: Une nouvelle approche pour la surveillance de la contamination des sols forestiers avec Cs-137 en Bavière, Allemagne

La catastrophe au Japon en 2011 nous rappelle le danger potentiel permanent lié à des centrales nucléaires et menaçant les écosystèmes mondiaux. Dans un premier temps, c'est le radionucléide Cs-137 qui produit des réservoirs de longue durée dans les sols sous forêt. Dès l'accident nucléaire grave de Tchernobyl en 1986, ce problème se manifeste dans des vastes zones forestières en Bavière et ceci jusqu'à nos jours. Les considérations du moment incluent aussi des différentes méthodes d'observation pour mesurer et documenter la concentration du Cs-137 dans les forêts. L'importance de la couche organique superficielle pour la mobilité et disponibilité du Cs-137 pour des plantes est prouvée par de nombreuses études. Jusqu'a présent, les programmes d'observation opérant en Bavière ne tiennent pas compte de ce fait, mais un nouveau concept fut créé récemment en coopération avec le Ministère Bavarois de l'Environnement et de la Santé. Les critères principaux du concept sont représentés par des paramètres géo-écologiques qui contribuent à la formation de la matière organique. Selon ce concept les forêts nationales sont divisées en plusieurs unités morpho-pédologiques. Puis, chacune d'elles est soumise a un procédé de sélection visant à évaluer la distribution des forêts de conifères et de feuillus, du relief raide ou plat et des étages du relief d'altitudes différentes. L'extension de chaque surface dépend de l'altitude, cela veut dire pour le relief montagneux 30 x 30 m, pour le relief plat 50 x 50 m. D'autres critères qui s'y ajoutent sont l'homogénéité des surfaces, le degré de surveillance, des informations détaillées locales, des distances aux stations de surveillance environnementale variables et, en tout, une distribution proportionnée. L'étude présente illustre la transformation du procédé de sélection basé à un SIG, y inclus une présentation des surfaces choisies pour l'observation permanente et des premiers résultats de la mobilité du Cs-137 dans les sols. En total 48 surfaces différentes étaient déterminées et documentées par le même nombre de profils de sol et par 96 monolithes et 96 échantillons de sol mixtes. Méthodiquement, on a profité beaucoup de l'usage d'un SIG. Les échantillons pris selon le standard AVV-IMIS (un échantillon de la matière organique et un du sol minéral, chacun composé de 30 sondages) démontrent que l'activité moyenne du CS-137 jusqu'à une profondeur de 30 cm fluctue fortement entre 31,78-1214,00 Bq kg^{-1} (couches organiques superficielles) et 5,68-232,00 Bq kg^{-1} (sols minéraux). Les résultats font preuve d'une distribution spatiale typique de l'activité du Cs-137 toujours forte dans la matière organique. Par ailleurs, le grand nombre de données collectionnées constitue une base solide pour des futures recherches en considération des facteurs dirigeants la distribution verticale du Cs-137 et sa disponibilité pour des plantes dans les sols sous forêt. De même, la méthode présentée dans cette étude peut être utilisée pour la recherche d'autres substances dangereuses déposées dans ces sols.

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