Rates of sheet and rill erosion in Germany — A meta-analysis

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ABSTRACT

Knowledge of erosion rates under real conditions is of great concern regarding sustainability of landuse and off-site effects on water bodies and settlements. Experimentally derived rates of sheet and rill erosion are often biased by experimental settings, which deviate considerably from typical landuse, by short measuring periods and by small spatial extensions, which do not account for the pronounced spatio-temporal variability of erosion events. We compiled data from 27 studies covering 1076 plot years to account for this variability. Modelling was used to correct for deficiencies in the experimental settings, which overrepresented arable land and used steeper and shorter slopes as well as higher erosivity than typically found in reality. For example, the average slope gradient was 5.9° for all arable plot experiments while it is only 2.6° on total arable land in Germany. The expected soil loss by sheet and rill erosion in Germany after taking real slopes, landuse and erosivity into account averaged 2.7 t ha^{-1} yr^{-1}. Annual crops contributed the largest proportion (90%) but hops despite its negligible contribution to landuse (0.06%) still contribute 1.0% due to its extraordinary rapid erosion, which was even faster than the measured bare fallow soil loss standardized to otherwise identical conditions. Bare fallow soil loss, which is often used as baseline, was 80 t ha^{-1} yr^{-1} when standardized to 5.1° slope gradient, 200 m flow path length, and average German erosivity.

1. Introduction

Soil erosion by water is regarded as the most important threat to the soil resources (Oldeman et al., 1991; Auerswald and Kutilek, 1998). It may be caused by water, wind, tillage or harvest of root crops. Water and tillage erosion contribute the largest proportion and affect by far the largest areas. While tillage erosion receives attention only since one to two decades ago (Lindstrom et al., 1992), water erosion has been recognized as a threat to the soil resource presumably since shortly after the onset of arable landuse. Despite this long experience with soil erosion by water and despite many attempts to quantify its extent, quantification can still be regarded as unsolved. The main reason for this deficiency is the pronounced stochastic character of erosion events. Higher and more intense rainfall is related to longer recurrence intervals. The recurrence interval, however, is only a statistical expression of highly variable rainfall events in time. Furthermore, highly erosive rains mostly cover only small areas. The hot spots of thunderstorm cells may have several hundred meters to a few kilometres in size (Aniol, 1975; Fiener and Auerswald, 2009). Finally, most crops leave the soil surface unprotected only in a certain period of the year. It is thus highly unlikely that these rare events can be represented in a statistically correct proportion in studies of limited temporal and spatial extent. Thus, the percentage of large events is either too large or too small in an individual study. The largest event within a given measuring period often dominates the total but also the average soil loss of this period. The wrong representation of large events thus leads to significant bias of actual soil loss data in different studies. Studying vineyards in Germany for instance, Emde (1992) found a mean soil loss of 151 t ha^{-1} yr^{-1} averaged over 10 plot years while Richter (1991) only measured 0.2 t ha^{-1} yr^{-1} averaged over 144 plot years. Environmental differences between the study areas or differences in vine cultivation cannot explain this difference. It was caused by the largest event during the study by Emde (1992), which obviously was overrated as compared to the size of his data set. Such an event was entirely missing in the much larger data set of Richter (1991).

Several approaches can be applied to overcome this deficiency: (i) Long-term measurement records can be set up but they are limited to a few locations and cannot account for the large spatial variability of soil erosion phenomena. (ii) Tracer studies, especially by using ^{137}Cs from nuclear bomb testing in the 1960s allow quantifying soil erosion since that time and at numerous locations, and thus overcome the problems of stochastic events. Unfortunately, this technique records soil loss without adequate process considerations. Erosion processes other than water and wind erosion, namely tillage erosion (De Alba

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et al., 2004) and harvest erosion (Poesen et al., 2001) also contribute to total soil loss and the contribution of these different processes has to be quantified by modelling. (iii) Modelling soil erosion processes again depends on representative data for model development and parameterization. Furthermore, models are always an issue of debate, whether they sufficiently reproduce reality. In this study we follow another approach to overcome the temporal limitations of individual studies and to estimate soil erosion for different landuse in the whole of Germany. To this end, all existing measured (and published) data sets from Germany are compiled and standardized and later on used in combination with national data sets of landuse, slopes and rain erosivity.

2. Regional setting

Germany is 357,031 km^2 in size with highly variable natural and anthropogenic conditions for soil erosion. Rural landuse cover comprises 37% arable land, 17% grassland and 30% forests, while urban and surface water areas cover 16% (Destatis, 2002). The northern part of Germany lies in the North European Lowlands (German part called North German Lowlands), with flat to gently undulated terrain crossed by north- to north-west-flowing watercourses (Fig. 1). Moving south, central Germany features a hilly countryside of low mountain ranges. The landscapes in Germany's southern part comprise upland ridges, Mesozoic escarplands, and the area of the Tertiary hills and Alpine moraines, where slopes in general are considerably steeper than in the northern lowlands. At the southern border to Austria and Switzerland, in a fringe of the Northern Alps, elevation reaches almost 3000 m and the steepest slopes occur, which are forested or occupied by pastures and natural meadows. Continental conditions increase from northwest to southeast Germany. In consequence, the frequency and severity of thunderstorms and the concentration of precipitation during summer months increase along this gradient and cause an increase in rainfall erosivity. This general trend is modified and further aggravated by topography, which induces an increase in precipitation from the flat lowlands in the North (approx. 500–800 mm yr^{-1}) to the mountain ridges in the centre (800–1200 mm yr^{-1}) and finally to the Alps in the South where precipitation peaks at more than 2000 mm yr^{-1}. Hence rainfall erosivity increases from 40 N h^{-1} yr^{-1} in the North-West to 100 N h^{-1} yr^{-1} in the South and even exceeds this value in the German Alps (Sauerborn, 1994).

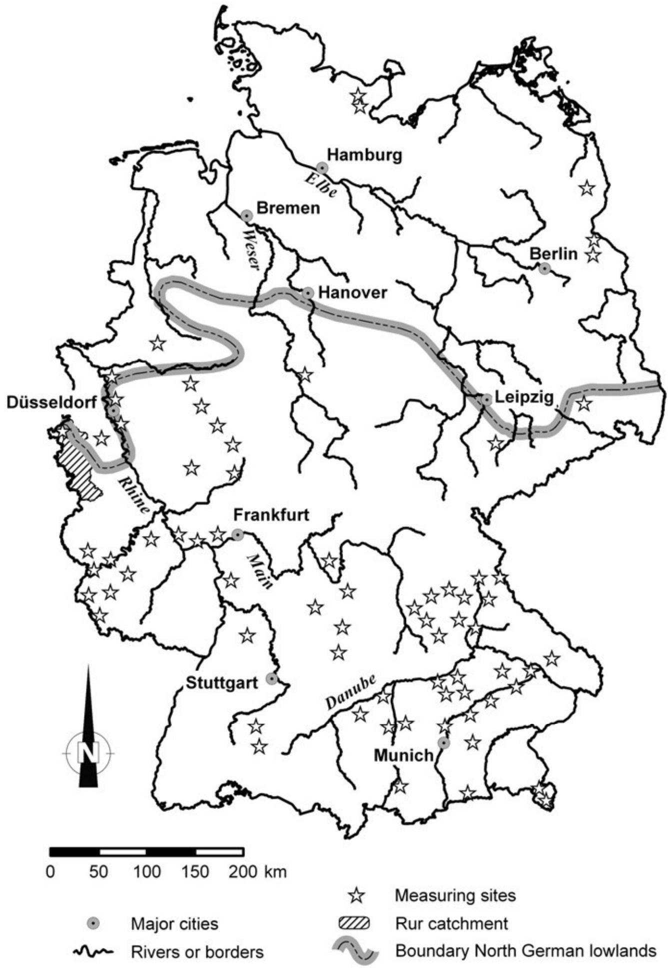

Fig. 1. Location of measuring sites; location is an approximation because most studies did not provide exact coordinates.

3. Materials and methods

3.1. Collection of measured data

Data from all available studies on soil loss under natural rainfall in Germany were compiled. Most data sets were from plot experiments, but also some tracer and small watershed studies were included. As the comparison of rainfall resulting from different simulation equipments with natural rainfall is more or less impossible, rainfall simulation studies were excluded. Moreover, sediment delivery data from larger watersheds with heterogeneous landuse were not included as no landuse-specific identification of sediment source areas is possible in these cases. Only published data were used while internal reports and theses below Ph.D. theses level were discarded. The results of the studies are summarized in Table 1. The results were combined according to landuse and weighted according to the length of the study period. Many studies did not cover only whole-year periods but also had partial years included. These data were also used and weighted according to the months of measurement to maximize the data set. These partial years mostly covered the growing period while the dormant season is slightly underrated in the data set. No correction was applied for this bias. A correction would have to be based on an assumption on seasonal changes in erosion rates. No reliable estimate of the seasonality was available because the contribution of snowmelt erosion during winter and early spring to total soil loss is unknown (Schwertmann et al., 1987). Such an estimate of seasonality could also not be derived from the data set itself. While seasonal distribution of rain erosivity indicates that rainstorms are much more severe during summer months with more than 80% of the erosivity falling between May and September (Schwertmann et al., 1987), there are also erosion measurements showing that erosion by winter runoff can be severe, because soil cover is low and moisture content is high (Saupe, 1990; Fiener and Auerswald, 2006).

In spite of the large number of studies (27) their setup cannot be regarded representative for Germany. Four major deficiencies exist: (i) Landuse did not reflect the actual landuse. Many studies used bare fallow plots as a baseline reference, which does not exist in reality. On the other hand, grassland and forests were largely underrated. (ii) Slope gradients did not reflect reality, e.g. flat land is missing. (iii) Plots were mostly very small in size compared to real fields. (iv) Plots were predominantly located in areas with relatively large rain erosivity. Furthermore, there was a consistent bias in the data because highly erodible surfaces were more often examined on shorter plots than low erodible surfaces, e.g. weighted average slope length was 11.2 m for bare fallow plots while it was 82.3 m for annual crop plots. Field, watershed or tracer data were completely missing for bare fallow treatment (Table 1).

To overcome the limitations of individual data sets and to derive representative soil erosion rates and a soil erosion map for Germany, the following methodology was applied extending and refining an approach used by Cerdan et al. (2006) for Europe.

Table 1

Measured soil losses due to sheet and rill erosion; although the table indicates comparability, this could not fully be achieved due to missing information, incomplete years of measurement, different approaches, unique situations and a lack of information about the expected return periods of the measured events in relation to the length of the observation period; to include studies with measuring periods other than one year, average monthly soil losses were calculated and multiplied by 12 to yield annual rates; no corrections were made for differences in slope gradient, plot length and size.

Location	Landuse	Slope (°)	Slope length (m)	Area (m^2)	Plot years	Type of study[a]	Soil texture[b] Sa/Si/Cl (%) bulk soil	Mean rainfall (mm yr^{-1})	Mean erosion (t ha^{-1} yr^{-1})	Reference[c]
Hohenpeißenb.	Arable crops	6.8	8	16	24.0	P	40/27/12	1304	0.3	J80
Albacher Hof	Arable crops	5.7	8	16	12.0	P	12/63/25	761	1.1	J80
Erndtebrück	Arable crops	6.0	8	16	44.0	P	19/42/7	652	0.3	J80
Marburg	Arable crops	5.1	8	16	24.0	P	45/44/7	1230	0.6	J80
Rauischholzh.	Arable crops	4.6	8	16	26.0	P	22/48/30	418	0.1	J80
Blumberg	Arable crops	8.5	8	16	9.0	P	37/25/12	809	0.8	J80
BE2	Barley	12.0	60	720	1.0	W	8/74/7	1100	0.7	D86
Müncheberg	Maize	6.8	65	293	2.5	P		525	23.3	B90
EH1	Maize	110.0	40	4 700	1.0	W	8/81/10	1100	36	D86
Dedelow	Maize	16.8	20	50	0.5	P		497	4.5	D89
Kiel	Maize	5.7	5.33	12	2.3	P	2 soils	750	4.6	G89a, b
Kiel	Maize + clover	5.7	5.33	12	2.3	P	2 soils	750	2.5	G89a, b
Scheyern	Mixed. organic farming	Av. 6.5	Av. 111	16 000–110 000	40.0	W	Different soils	834	0.2	A03
Scheyern	Mixed. with mulch tillage	Av. 5.1	Av. 159	8000–160 000	60.0	W	Different soils	834	2.5	A03
EH1	Oat	110.0	60	7000	1.0	W	8/81/10	1100	1.5	D86
Taunus	Rotation	4.6–7.4	8	16	5.0	P	6/77/16	650	5.6	V78
Müncheberg	Row crop	5.1–5.7	50		5.0	P		525	35.2	F98
Dedelow	Row crop	6.3–8.0	20		2.4	P		497	5.0	F98
Dedelow	Rye	6.8	20	50	0.5	P		497	0.4	D89
Obersdorf	Small grain	7.4	20	50	9.0	P		531	1.4	D94
Dedelow	Small grain	6.3–8.0	20		2.4	P		497	0.4	F98
Scheyern	Small grain	11.3		20 000	23.0	T	20/30/18	725	14	S02
Odenwald	Small grain	2.3–4.6	8	16	5.0	P	2 soils	780	0.19	V78
Tarforst	Spring barley	4.6	8	8	3.0	P		680	0.1	R87
Olewig	Spring barley	4.6	8	8	3.0	P		465	0.0	R87
Kockelsberg	Spring barley	4.6	8	8	3.0	P		718	0.1	R87
Bitbg. Ch.	Spring barley	4.6	8	8	3.0	P		765	0.1	R87
Hungelsberg	Spring barley	4.6	8	8	3.0	P		775	0.1	R87
Dickes Kreuz	Spring barley	4.6	8	8	3.0	P		1042	0.0	R87
EH1	Sugar beet	10.0	60	6100	1.0	W	8/81/10	1100	458	D86
Dölzig	Sugar beet	4.6–5.1	85–325	2000–9000	10	P		600	230.8	S92
ZI1	Wheat	6.5	165	2145	1.0	W	8/74/7	1100	0.2	D86
Kiel	Wheat	5.1–15.1	8	16	2.4	P		750	0.7	F00
Ostrau	Wheat	2.9–11.3	60–250		5.0	P			103.4	S90
Euchen	Bare fallow	4.3	10	15	0.9	P	4/75/21	569	22.1	B91
Niederkasten.	Bare fallow	2.9	10	15	0.9	P	20/46/17	550	38.0	B91
Eschmar	Bare fallow	7.7	10	15	0.9	P	71/14/10	632	140.6	B91
Saalhausen	Bare fallow	10.5	10	15	0.5	P	18/39/13	780	1.3	B91
Hochdahl	Bare fallow	4.6	10	15	0.6	P	63/30/7	842	42.1	B91
Werden	Bare fallow	2.9	10	15	0.8	P	6/78/16		6.0	B91
Soest	Bare fallow	3.4	10	15	0.9	P	4/71/20		0.5	B91
Nottuln	Bare fallow	3.4	10	15	0.7	P	38/37/20	692	7.7	B91
Schwäb. Alb	Bare fallow	3.4			5.0	P			13.9	D68
Hollmuth	Bare fallow	13.1	5	10	3.0	P	17/75/14	885	1.7	D86
Hollmuth	Bare fallow	13.1	2	4	3.0	P	17/75/14	885	49.8	D86
Hollmuth	Bare fallow	13.1	2	4	3.0	P	17/75/14	885	33.8	D86

Hollmuth	Bare fallow	13.2	5	10	3.0	P	17/75/14	885	37.2	D86
Hollmuth	Bare fallow	12.5	10	20	3.0	P	17/75/14	885	19.7	D86
Hollmuth	Bare fallow	12.5	20	40	3.0	P	17/75/14	885	18.3	D86
Dedelow	Bare fallow	6.8	20	50	0.5	P		497	3.5	D89
Obersdorf	Bare fallow	7.4	20	50	9.0	P		531	8.2	D94
Dedelow	Bare fallow	6.3–8.0	20		2.4	P		497	21.9	F98
Kiel	Bare fallow	5.7	5.33	12	2.3	P	2 soils	750	5.4	G89a, b
Hohenpeißenb.	Bare fallow	6.8	8	16	5.0	P	40/27/12	1304	2.5	J80
Albacher Hof	Bare fallow	5.7	8	16	28.0	P	12/63/25	761	2.2	J80
Erndtebrück	Bare fallow	6.0	8	16	12.0	P	19/42/7	652	0.7	J80
Marburg	Bare fallow	5.1	8	16	13.0	P	45/44/7	1230	6.4	J80
Rauischholzh.	Bare fallow	4.6	8	16	9.0	P	22/48/30	418	1.6	J80
Blumberg	Bare fallow	8.5	8	16	6.0	P	37/25/12	809	3.6	J80
Albacher Hof	Bare fallow	6.3	8	16	5.0	P	12/63/25	761	8.0	K56
Marburg	Bare fallow	5.1	8	16	2.0	P	45/44/7	1230	6.2	K56
Tertiary hills[d]	Bare fallow	5.4	8	8	70.0	P	14 soils	725	35.8	M88, A93
Escarpland[d]	Bare fallow	5.4	8	8	60.0	P	12 soils	725	31.2	M88, A93
Mountain ridges[d]	Bare fallow	5.4	8	8	20.0	P	4 soils	725	24.2	M88, A93
Moraines[d]	Bare fallow	5.4	8	8	10.0	P	2 soils	725	15.6	M88, A93
Mittelgebirge	Bare fallow	4.6			3.0	P			2.9	P77
Tarforst	Bare fallow	4.6	8	8	2.0	P		680	0.5	R87
Olewig	Bare fallow	4.6	8	8	2.0	P		465	1.8	R87
Kockelsberg	Bare fallow	4.6	8	8	2.0	P		718	1.1	R87
Bitbg. Ch.	Bare fallow	4.6	8	8	2.0	P		765	1.8	R87
Hungelsberg	Bare fallow	4.6	8	8	2.0	P		775	3.2	R87
Dickes Kreuz	Bare fallow	4.6	8	8	0.5	P		1042	2.6	R87
Königsbach	Pasture	19.8	40	186	0.4	P		1065	0.0006	F93
Jenner	Pasture	24.2	40	182	0.4	P		1065	0.012	F93
Brunnen	Pasture	19.8		18000	0.4	W		1065	0.48	F93
Kaser	Pasture	19.8		2977	0.4	W		1065	0.34	F93
Grat	Pasture	18.8		301	0.4	W		1065	0.016	F93
Königstal	Pasture	33.0	40	167	0.4	P		1065	0.001	F93
Odenwald	Meadow		8	16	5.0	P	2 soils	780	0.19	V78
Tegernsee	Forest	18.8–20.8	40	200	8.0	P		1700	0.0001	A95
Wald	Forest	30.1		577	0.4	W		1065	0.0002	F93
Odenwald	Forest		8	16	5.0	P	2 soils	780	0.003	V78
Steinberg	Vines	17.8	100		14.0	P			28.0	E05
Geisenheim	Vines	5.7–17.8	100		10.0	P	2 soils	625	151	E92
Geisenheim	Vines	5.7–17.8	70		1.0	P	45/23/12	625	12.4	E92
Geisenheim	Vines	5.7–17.8	30		1.0	P	45/23/12	625	3.1	E92
Geisenheim	Vines + grass	5.7–17.8	100		5.0	P	45/23/12	625	0.001	E92
Mertesdorf	Vines	20.8	8/16		168.0	P	31/19/11	602	0.2	R91
Mainburg	Hops	2.7	45		45.0	T	25/50/16	750	52	S80
Au	Hops	3.4	65		34.0	T	24/49/23	750	55	S80
Au	Hops	1.4	70		45.0	T	27/55/10	750	15	S80
Geroldshausen	Hops	2.6	130		31.0	T	18/60/16	750	77	S80
Geroldshausen	Hops	3.6	210		22.0	T	56/28/9	750	205	S80
Au	Hops	2.6	50		45.0	T	28/50/14	750	24	S80

[a] P: Plots, T: Tracer, W: Fields, small watersheds.

[b] Sa: Sand>0.63 mm, Si: Silt, Cl: Clay<2 µm.

[c] References: A03: Auerswald et al. (2003), A93: Auerswald (1993), A95: Ammer et al. (1995), B90: Barkusky (1990), B91: Botschek (1991), D68: Dubber (1968), D86: Dikau (1986), D89: Deumlich and Gödicke (1989), D94: Deumlich and Frielinghaus (1994), E92: Emde (1992), E05: Emde et al. (2005), F00: Fleige and Horn (2000), F93: Felix and Johannes (1993), F98: Frielinghaus (1998), G89a: Goeck (1989), G89b: Goeck and Geisler (1989), J80: Jung and Brechtel (1980), K56: Kuron et al. (1956), M88: Martin (1988), P77: Preuss (1977), R87: Richter (1987), R91: Richter (1991), S80: Schwertmann and Schmidt (1980) recalculated (this article), S90: Saupe (1990), S92: Saupe (1992), S02: Schimmack et al. (2002), V78: Voss (1978).

[d] Measurements from different landscapes in Southern Germany.

3.2. Aggregation of landuse categories

The data of the different studies were categorized to get similar landuse categories as those available on a national scale (ECC, 1992; Destatis, 2002). These landuse categories are annual arable land (including all data from annual crops), grassland and forest; and due to the specific location on steep slopes vineyards; and regarding their high erosion potential hop gardens. As no measured data are available for urban areas and settlements, these landuse categories were excluded from further analysis.

Within landuse category ‘annual arable land’ most studies had a setup consisting of a plot treatment close to current landuse and additionally other treatments to achieve a wide variety of conditions. These additional treatments often included a bare fallow plot as the worst-case scenario and one or more soil conservation practices. Except for these studies aiming to determine soil erodibility (especially Martin, 1988; Auerswald, 1993) these bare fallow treatments did not follow the recommendations of Wischmeier (1960) and Wischmeier and Smith (1978), who did not use data of the first two years of bare fallow because these years are still heavily influenced by carry-over effects of the preceding crops. Soil conservation measures applied on other plots do not occupy relevant acreages under German farming conditions. Deleting the bare fallow plots (<2 yr fallow) and soil conservation plots from the data set would have reduced the number of years considerably while deleting only one of these two groups would have biased the averages. We hence used all arable plots to account for the range in arable landuse conditions and to base our results on a wide data set assuming that the biases caused by bare fallow and by soil conservation systems almost level out. However, studies using long-term bare fallow (>2 yr) aiming to determine soil erodibility were deleted from the data set of annual arable land and will be reported as a separate, additional landuse category ‘bare fallow’, which quantifies the natural soil erosion disposition without cropping influence. These long-term bare fallow studies were available only from a few sites although they comprised a large number of plot years. To base the average soil loss for the bare fallow category on a regionally wider data set, the bare fallow plots of the annual arable landuse studies (<2 yr) were also included but these were corrected in this case by dividing them by 0.8, which is a correction factor recommended by Wischmeier and Smith (1978) to account for prior landuse effects. The category ‘bare fallow’ still is dominated by studies, which followed the definition by Wischmeier and Smith (1978) and thus this assumption will introduce only small error.

3.3. Adjustment for landuse

To derive an areal distribution of the above categorized landuses (except hop gardens and fallow land) on a national scale, the European CORINE data set (COoRdination of INformation on the Environment; ECC, 1992) was used, which provides 44 classes of land cover data at a scale 1:100 000 mostly derived from the exploration of satellite images together with other relevant documents. The original CORINE classification for landuses found in rural areas of Germany and the aggregation of these into the categories annual arable land, grassland, forests and vineyards are shown in Table 2. Difficulties in assigning a proper landuse category arose especially for class 243 (Land principally occupied by agriculture, with significant areas of natural vegetation), which contributed 2.1% of the total area. It was evenly distributed between forests and grassland. The error of this assumption should be small given the small contribution of this class to the total area and the similarity in erosion potential of forests and grasslands. Further, the class “Fruit trees and berry plantations” occupying 0.4% was evenly distributed between arable land and forests, because no measurements were available for this land use. In summary, this approach led to a distribution of rural landuse similar to the distribution derived from official statistics (Table 2; Desatis, 2002).

3.4. Adjustment for slope gradients

To account for a slope gradient distribution throughout Germany, slope gradients were derived from the SRTM (Shuttle Radar Topography Mission) digital elevation model (Rabus et al., 2003). This digital elevation data have an absolute horizontal and vertical accuracy of 20 m (circular error at 90% confidence) and 16 m (linear error at 90% confidence), respectively. The data files are freely available at a NASA file server (ftp://e0mss21u.ecs.nasa.gov/srtm/). They were processed and transformed to a raster map with 75 × 75 m resolution using the software package ArcGIS 9.2 (ESRI, USA). To quantify a potential bias in slopes due to a smoothening of steep and short slopes in low resolution digital elevation models (Guth, 2006) we compared the SRTM DEM with a high resolution 10 × 10 m laser scanner DEM (Landesvermessungsamt, North-Rhine-Westphalia) of the Rur catchment (2354 km^2) located southwest of Düsseldorf (Fig. 1).

The slope gradients were converted to the S factor of the USLE, which is the dimensionless influence of slope gradient as compared to a baseline gradient of 5.1° (=9%). The equation by Nearing (1997) was used to calculate S because it is applicable also for steep slopes as commonly found in vineyards, grasslands and forests.

$$S = -1.5 + \frac{17}{1 + e^{2.3 - 6.1\sin(\alpha)}} \tag{1}$$

where S is the slope factor of the USLE [–] and α is the slope gradient [°].

Table 2

CORINE (ECC, 1992) land cover areas for Germany used to derive the landuse categories applied in this study; only those data representing rural areas were taken from the CORINE data set and are compared to German landuse statistics (Destatis, 2002); urban areas and water surfaces are not included.

Landuse categories	Landuse according to the CORINE data set	Area of CORINE landuses (%)	Area of landuse categories aggregated from CORINE (%)	Area of landuse categories according to statistics (%)
Annual arable land	Non-irrigated arable land	39.9	39.9	36.9
Grassland	Pastures and meadows	12.0		
	Complex cultivation pattern	5.7		
	Natural grassland	0.1		
	Moors and heath land	0.3		
	Land principally occupied by agriculture with significant areas of natural vegetation	1.1	19.2	16.9
Forests	Broad-leaved forest	6.6		
	Coniferous forest	15.9		
	Mixed forest	6.7		
	Land principally occupied by agriculture with significant areas of natural vegetation	1.1	30.3	29.9
Vineyards	Vineyards	0.4	0.4	0.3
Hop gardens	–	–	–	0.1

Eq. (1) was also used to standardize the measured soil losses from the individual plots to an expected loss for the baseline gradient.

3.5. Adjustment for flow path length

To account for the difference in flow path length between plot data and the real field situation, no appropriate data set exists. Even if one would derive data for field situations from a combination of the SRTM digital elevation model and the CORINE data set, results would be biased by the problem of missing data regarding the existing channel systems between fields and/or patchiness of fields, which both can substantially shorten flow path length. However, although no appropriate statistical data on flow path length exists, it is larger in most cases than the average plot length calculated from the evaluated studies (Table 1). Therefore, we applied a second step of standardization in correcting the measured data to a slope length of 200 m, which seems to be closer to reality under German farming conditions than the actual plot lengths. To this end, Eq. (2) provided by Wischmeier and Smith (1978) was used applying an exponent m of 0.5 for slopes $>2.9°$ and utilizing Eq. (3) from Murphree and Mutchler (1981) for smaller slopes:

$$L = \left(\frac{\lambda}{22.1}\right)^{m} \tag{2}$$

$$m = 1.2 \cdot (\sin\alpha)^{1/3} \tag{3}$$

where L is the slope length factor of the USLE [–], λ is slope length [m], and α is the slope gradient [°].

Although this procedure is unsatisfactory, it will lead to values, which should be closer to reality than the uncorrected values. The procedure will also allow adjusting the data set to reality easily once data on flow path lengths are available. For vineyards an erosive slope length of 200 m seems to be unrealistic. In a detailed study visiting all vineyards in Bavaria, Königer and Schwab (2000, 2002) identified typical slope lengths of 60 m for linkage-pull vineyards ("Steillagen") and 80 m for tractor-pull vineyards ("Direktzuglagen"), which are flatter than linkage-pull vineyards. This corresponds to L factors of 1.65 and 1.90, respectively. Linkage-pull and tractor-pull vineyards contribute 17% and 83%, respectively, to total vineyard area in Germany. We hence used an area weighted average L factor of 1.86 for vineyards.

3.6. Adjustment for rain erosivity

After standardization for slope gradient and slope length the measured data were standardized in a third step to account for regional differences in rain erosivity using an R factor map of Germany based on high-resolution and long-term rainfall data measured at 139 meteorological stations (Sauerborn, 1994). As most studies did not report the R factor for the measuring period or the data necessary to calculate it, this standardization could only be applied for the long-term average but not for the individual measuring period.

3.7. Adjustment for hops

The procedure (Section 3.3) could not be applied to hop gardens for two reasons. First, hops cannot be identified in the CORINE data set (Table 2), and second, only tracer data from fields were available from Schwertmann and Schmidt (1980), who did not distinguish between water erosion and tillage erosion at that time. However, hops are a crop especially prone to erosion and the largest hop growing area in the world (the Hallertau) is located in southern Germany (Knoll and Sieber, 1986). Hence, hops could not be omitted or assigned to any other landuse category. To distinguish between water and tillage erosion, the original data of Schmidt (1979) were used, which quantify the tracer distribution (copper in this case) over soil depth along slope transects. Accumulations at the foot slope could clearly be detected although sedimentation from water erosion is highly unlikely on these straight slopes. We assumed that the accumulations resulted from tillage erosion and are balanced by an equivalent loss from the eroding area. The total erosion reported by Schwertmann and Schmidt (1980) could thus be attributed to a tillage-induced or water-induced portion (Table 3). To determine a slope gradient distribution, the hop gardens were identified in the official surveying and cadastral information system ATKIS (Amtliches Topographisches Kataster-Informations-System; Steudle, 1997) and the slope gradients were calculated from a more detailed 50-m grid digital elevation model, which was available for the hops area. No correction for slope length was applied assuming that the hop gardens analyzed by Schmidt (1979) reflected reality in this respect (weighted average slope length: 82 m), although they seem to be somewhat shorter than average. This may be caused by the selection of homogeneous, straight slopes in the study of Schwertmann and Schmidt (1980). On the other hand, more erosion-reducing measures are found in hop gardens now (Auerswald et al., 2003) as compared to the time when the erosion in the hop gardens was analyzed by Schwertmann and Schmidt (1980). No quantitative estimate of both effects exists but they should at least partly compensate each other. Hence we used the data from hop gardens without correction for actual slope length and actual erosion control measures.

3.8. Combinations of adjustments in a national map

The procedures (Section 3.2) to (Section 3.7) were combined to derive a national soil erosion map for Germany and to calculate the average erosion rates for each land use category. To this end, standardized erosion rates of each landuse category were combined with the generalized CORINE land cover data and these standardized rates were multiplied with S, relative L (slope specific L factor divided by L factor for standard slope of 5.1°) and relative R (R factor divided by mean R) for each 75 × 75 m raster cell. To include hop gardens the standardized erosion rates of hops were multiplied with S, relative R and the proportion of hops in each raster cell. In a last step the erosion map using the CORINE data was multiplied with the proportion of landuse excluding hops, and the hops erosion map was added. No correction for soil properties was applied assuming that the measurements within the land use categories arable land, vineyards, hops, grassland and forests have been carried out on soils typical for these land uses.

4. Results and discussion

4.1. Distribution of measuring sites

Most data were derived from locations in southern and western Germany (Fig. 1), while data from northern and eastern Germany were less frequent. This scarcity of data is mainly caused by the mostly

Table 3
Water and tillage erosion in hop gardens as estimated from long-term copper budgets; recalculated and assigned to water and tillage erosion separately using the raw data taken from Schmidt (1979); averages are weighted for years.

Field no.	Number of years	Slope gradient (°)	Slope length (m)	Water erosion (t ha^{-1} yr^{-1})	Tillage erosion (t ha^{-1} yr^{-1})	Total erosion (t ha^{-1} yr^{-1})
1	45	2.7	45	52	38	90
2	34	3.4	65	55	39	94
3	45	1.4	70	15	27	42
4	31	2.6	130	77	42	119
5	22	3.6	210	205	63	268
6	45	2.6	50	24	32	56
Average	37	2.7	95	58	38	96

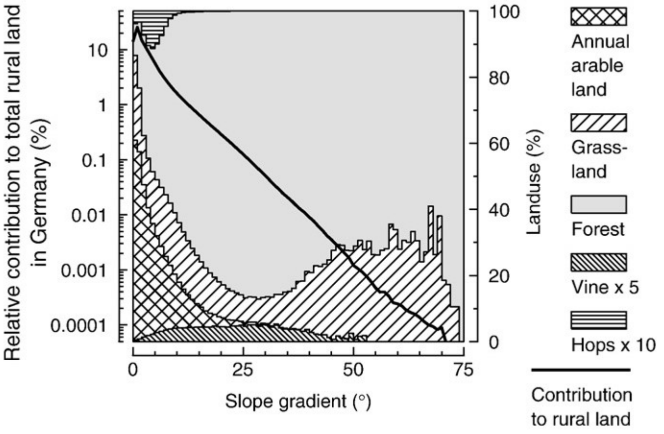

Fig. 2. Contribution of slope gradient classes to total rural land (bold line and left *y* axis) and distribution of landuse among slope gradient classes (right *y* axis and shaded areas; vine is inflated by a factor of 5, hops by 10).

flat terrain in the North German Lowlands, where comparably little sheet and rill erosion is expected due to the low slope gradients. Little error can be expected from the scarcity of data in these areas because the correction for slope gradient and rain erosivity also predicts small soil losses. A large relative error in these areas will have little absolute effect on the country-wide averages, which are dominated by the more erosive sites.

Analogously, those landuses are also greatly underrated in the data set for which little erosion can be expected (grassland, forest). Again this should have comparably little effect on the accuracy of the country-wide average due to their small contribution to total soil loss.

4.2. Distribution of landuse among slope gradients

According to the SRTM and the CORINE data sets, annual arable land can be mainly found on sites with slope gradients <4° (Fig. 2). Vineyards are preferably established on slopes ranging from 10° to 30°, while hop gardens only occupy comparably flat areas with slopes around 3°. The proportion of grassland is more or less constant on slopes <30° but increases on steeper slopes due to the steep pastures and natural meadows in mountainous and alpine areas. Forests occupy the steepest parts of the country and are in general dominating slopes >4°.

The appearance of Fig. 2 is somewhat misleading, as slope gradients larger than 4° contribute only 25% to total rural land, while Fig. 2 also reports the distribution of landuse for slope gradients up to 75° and thus seems to inflate the proportion of forest and grassland. The average slopes of the landuse categories (Table 4) are hence much lower than it may be expected from Fig. 2. The skew in the distribution of slope gradients also becomes obvious from the comparison of the median and mean slope (Table 4), where the median is only about half of the mean. The mean slope is largest for vineyards due to the lack of vineyards on flat terrain and it is smallest for hop gardens. From the difference in slope gradients it can be expected that forest and vineyard sites are 3 to 4 times more prone to erosion than arable sites, while grassland and arable sites differ by less than a factor of 2.

The slope gradients from the plot data greatly deviate from the country averages (Table 4). Researchers mainly examined slopes which were steeper than the typical situation of a certain landuse. On the other hand, they used unrealistically short and small plots (Table 1). There is clearly a demand for more realistic experimental setups because the extrapolation of the experimental results to reality thus depends on the applicability and accuracy of erosion models, which again are mainly developed from experiments using similar setups.

4.3. Distribution of landuse among rain erosivity

On average the rural area in Germany has approximately an *R* factor of 58 (standard deviation SD = 18 N h^{-1} yr^{-1}). This value is later on used to standardize the plot measurements, because these measurements were, analogously to slope gradients, mostly undertaken in areas with a higher erosivity compared to the average (Table 4). In vine growing areas average erosivity is slightly lower (Average AVR = 52, SD = 9 N h^{-1} yr^{-1}) while in hop gardens, which are located exclusively in southern Germany, average erosivity is slightly higher (AVR = 65, SD = 6 N h^{-1} yr^{-1}). For grassland and forests average rain erosivity is approximately 62 N h^{-1} yr^{-1}, with a more pronounced variability (SD is 21 N h^{-1} yr^{-1} in both cases) because these can be predominantly found in the climatically extreme sites. The German mean erosivities deviate substantially from the means of the plot experiments (Table 4). This is especially evident for vine (52 vs. 44) and forests (63 vs. 103).

4.4. Standardized soil loss

The standardized soil loss (slope 5.1°, slope length 200 m, average *R* factor of 58) of annual arable land was 15.2 t ha^{-1} yr^{-1}. Soil loss from row crops without any conservation measures averaged 88.6 t ha^{-1} yr^{-1} (34.1 plot years) and was considerably higher than the soil loss from short-term bare fallow (34.9 t ha^{-1} yr^{-1}, 63 plot years). Including short-term bare fallow into landuse category annual arable land, to compensate for the super proportional contribution of plots with conservation measures, thus seems to be justified. These short-term bare fallow plots contribute only 14% of total plot years.

Bare fallow soil loss from long-term experiments (240 plot years) was considerably larger than that from short-term bare fallow (63 plot years) even after adjustment for carry-over effects on the short-term plots (84.3 vs. 43.6 t ha^{-1} yr^{-1}). This indicates that the carry-over effect was underrated or that the sites of the short-term experiments were less prone to erosion although this is not evident from the available information. While the first argument would call for deleting the short-term data from the bare fallow average, the second

Table 4
Characteristics of slope, slope factor *S* of the USLE, and rainfall erosivity *R* in the experimental studies and for rural land throughout Germany; nationwide data are derived from a digital elevation model with 75 m resolution and from a rain erosivity map (Sauerborn, 1994); experimental studies are weighted for plot years; bare fallow slope and rain erosivity is calculated using data of the total rural land.

Property	Unit	Data base	Landuse					
			Bare fallow	Arable land	Grassland	Forests	Vineyards	Hop gardens
Average slope	(°)	Experiments	6.1	5.9	10.6	18.9	15.9	2.6
	(°)	Germany	4.4	2.6	3.9	7.0	7.3	3.4
Median slope	(°)	Germany	2.9	1.4	1.6	4.5	5.0	1.2
Average *S*	(–)	Experiments	0.92	0.46	1.56	0.77	1.65	0.6
	(–)	Germany	0.84	0.4	0.71	1.5	1.52	0.65
Average *R*	(N h^{-1} yr^{-1})	Experiments	67	64	66	103	44	69
	(N h^{-1} yr^{-1})	Germany	58	53	62	63	52	65

argument calls for the opposite. We kept the short-term results in the data set considering their comparably small contribution to the total number of plot years (21%).

Site conditions (soils, climate) were almost identical for bare fallow and annual arable crops because both were often examined at the same sites. Comparing the standardized soil loss shows that annual arable crops on average reduced soil loss to 14.9% of the long-term bare fallow soil loss. This is close to an estimate following a completely independent approach of modelling (13.2%) by Auerswald et al. (2003).

Standardized soil loss was considerably lower for vineyards than for annual arable land (Table 5), which is mainly caused by differences in soil properties (especially stoniness of vineyards) but might be also influenced by those in general different management operations.

In contrast, soil loss under hops was considerably higher. The data of Schwertmann and Schmidt (1980) indicated an average total soil loss of 96 t ha^{-1} yr^{-1} for hops for which two thirds could be attributed to water erosion and one third to tillage erosion (Table 3). The soil loss of hop gardens after adjusting to 5.1° slope gradient, 200 m slope length and average R factor was considerably greater than the soil loss of long-term bare fallow, which is surprising. This may be attributed to several effects: (i) It may indicate that hops even increase soil erosion above bare fallow, which, in terms of the USLE, would correspond to a C factor larger than 1. This could be caused by soil compaction due to frequent trafficking and by the effect of the large falling height of drops dripping off the leaves (~6 m). Especially during low-intensity rains with small drops these will be collected by the leaves and drip off as large drops (Brandt, 1989), which then gain considerable kinetic energy due to the large falling height as final crop height is 6 m with almost no leaves lower than 1 m above ground. Low-intensity rain prevail in Germany, where even the maximum 30-min intensity of erosive rains averages to only about 11 mm h^{-1} (Rogler, 1981). (ii) The correction factor L used to adjust bare fallow soil loss may underrate the slope length effect as compared to hops. This would especially be the case if hop gardens were subject to heavy rilling (McCool et al., 1997). (iii) The sites used for hop gardens may have more erodible soils than the average erodibilities of the bare fallow plots. (iv) The computed soil loss rates of the hop gardens may still be too high even after consideration of tillage erosion as they are determined from tracer losses. In this case, copper was used as a tracer, which at that time was applied as a fungicide with a uniform treatment scheme. The copper sulphate was applied to the leaves and some copper may be washed from the leaves and lost by runoff without being associated with a corresponding soil loss (Schwertmann and Schmidt, 1980). Presently it cannot be decided to which degree these explanations contribute to the higher soil loss under hops than under bare fallow.

Soil losses from forests and grassland were less than one tenth of the soil loss from annual arable land. Whether the difference between forest and grassland holds true is questionable due to the extraordinary short experimental record for both landuse classes.

4.5. Actual soil loss

The expected average soil loss by sheet and rill erosion in rural areas in Germany after adjustment for real slope gradients and distribution of landuse becomes 2.7 t ha^{-1} yr^{-1} and is based on 836 experimental plot years (Table 5). Annual arable crops contribute the largest share to this soil loss, but hops despite their negligible contribution to landuse (0.06%) still contribute 1.0% due to their extraordinary large erosion.

The spatial distribution of soil loss in Germany (Fig. 3) exhibits soil losses of 0–1 t ha^{-1} a^{-1} mainly in areas covered by grassland and forest (e.g. typical for the mountain ranges in central Germany) or in flat terrain of flood plains along larger rivers. Highest erosion rates > 10 t ha^{-1} a^{-1} are located in arable areas with relatively steep slopes. This causes a clear regional difference in water erosion between arable areas in the North German Lowlands and the hilly countryside of low mountain ranges in central Germany and the hilly areas of the Tertiary hills and Alpine moraines in southern Germany. The highest erosion rates concentrate in the hop growing area of Hallertau, north of Munich.

4.6. Validity of assumptions

The analysis is based on two assumptions. First, a long measuring period obtained by aggregating many studies can level out the pronounced variability of erosion events. Second, the soil loss rates, which were measured under non-representative conditions, can be standardized to typical conditions in Germany depending on landuse using S, L and R of the Universal Soil Loss Equation. It is helpful to prove both assumptions although the first is trivial and the second assumption makes use of the by far most often used soil erosion modelling tool for multi-year data. This proof cannot be conducted for the whole data set, which is statistically biased in many respects. Regarding the first assumption long-term data are mainly available for hops, while short-term data dominate for forests, which leads to an apparent but non-existing increase in soil loss with measuring period. The largest unbiased subset of data to prove the first assumption comes from annual arable crops, for which also the largest intra- and inter-annual variability can also be expected due to the varying soil cover and management. We can hence best examine the first assumption based on this subset. Short-term measurements (<3 yr) exhibited a pronounced variability covering five orders of magnitude, which decreased to about one order of magnitude with increasing number of plot years of the individual studies (Fig. 4) proving the first assumption. This convergence was still considerably weaker than what would be expected from generating long-term data by applying Monte-Carlo simulations to the short-term data. In such simulations the variability converges to less than one order of magnitude already after 20 yr (not shown). A main cause of variability results from the magnitude and timing of erosive rains. This variability cannot be covered by examining many vicinal plots over a short period of time

Table 5
Standardized erosion from plot experiments (standardization by weighting for plot years, R factor relative to the German average of 58 N h^{-1} yr^{-1}, slope gradient of 5.1° and an erosive slope length of 200 m) and expected average soil loss for Germany; calculated according to the raster data of slope gradients and erosivities assuming a slope length of 200 m for annual arable land, grassland and forests, while slope lengths of 80 m and 82 m are assumed for vineyards and hops.

	Plot experiments		Germany			
	Standardized erosion (200 m, 5.1° [9%], R = 58 N h^{-1} yr^{-1}) (t ha^{-1} yr^{-1})	Observation period (yr)	Average soil loss (t ha^{-1} yr^{-1})	Standard deviation of soil loss (t ha^{-1} yr^{-1})	Contribution to rural landuse (%)	Contribution to total soil loss (%)
Bare fallow	79.64	303.0				
Annual arable land	15.15	416.2	5.7	8.6	44.0	92.8
Grassland	0.48	9.4	0.5	2.3	20.2	3.7
Forests	0.01	13.4	0.2	2.6	35.7	2.6
Vineyards	5.44	175.0	5.2	5.9	0.34	0.7
Hop gardens	154.40	222.0	42.8	45.9	0.06	1.0
Total without bare fallow		836.0	2.7[a]			

[a] Expected average soil erosion for rural areas in Germany taking into account the area distribution of the different landuses.

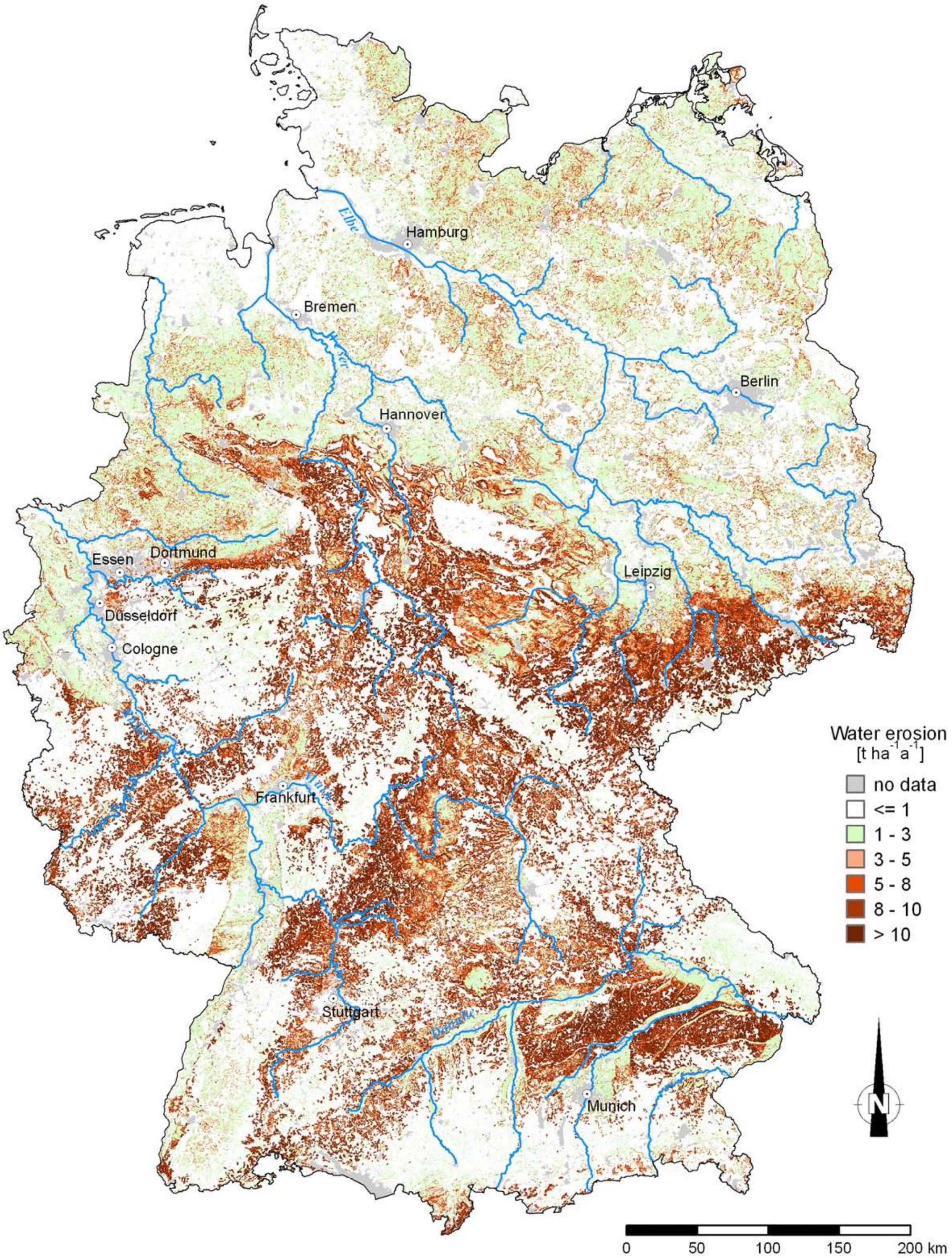

Fig. 3. Soil erosion map for Germany based on standardized soil erosion measurements of different landuse categories (836 yr of observation) and 75 × 75 m raster data for slope.

and hence variability decreases less with the number of plot years than with the number of years. Long-term datasets covering more than 20 yr do not exist for annual arable crops in Germany and can only be created by aggregating data from several studies.

Regarding the proof of the second assumption, the complete data set is also biased, which mainly relates to the lacking ability to measure very low or very high erosion rates. Hence, researchers aiming to measure soil surfaces with good protection select steep, long slopes while the opposite is true for surfaces with little protection, which results in a compensation or even reversion of the apparent effects of topography in the total dataset. The influence of slope gradient and length can hence best be analyzed on long-term data under identical landuse. These conditions are perfectly met by the data from the hop gardens, which were also similar regarding soil erodibility and rain erosivity but included a considerable variation in slope length and gradient. The *L* factor varied 2.1-fold between 1.30 and 2.68 while *S* varied 2.6-fold between 0.27 and 0.67. The combination of both factors almost perfectly explained the variation in soil loss between the different hop gardens (Fig. 5).

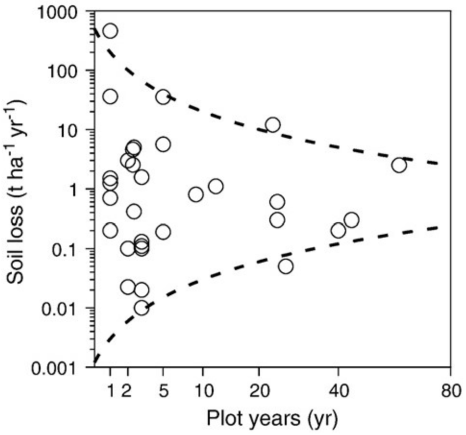

Fig. 4. Mean reported soil loss of annual arable crops of different studies ($n=32$) depending on the number of plot years; the lines denote arbitrarily chosen symmetrical hyperboles.

Even if the model being used to adjust the erosions rates works well, wrong estimates could still result if the data base used for the adjustment contains errors. Such errors can especially be expected for the SRTM slopes due to the coarse 75 × 75 m grid. Comparing slope distributions of the SRTM and the 10 × 10 m laser scanner DEM to determine a potential smoothening of steep slopes in the case of the low resolution data exhibited some unexpected results (Fig. 6). The laser scanner DEM had higher percentages of low slope gradients than the low resolution grid and no smoothening effects of steep and short slopes could be found in the SRTM data. The smaller percentage of low slope gradients in the SRTM data may result from noise in the radar data. The reason for a missing smoothing effect is unknown. Both effects are considerably smaller for arable land, which contributes most to erosion. No correction was applied considering the unknown source of the effect and the general uncertainty when retrieving slope gradients from a DEM. Warren et al. (2004) have shown that, even if the DEM is dense and accurately obtained by a geodetic survey, errors in slope calculation may cause errors in erosion by a factor of ten.

4.7. Restrictions of the erosion data base

Accuracy of the average soil loss from annual crops should increase considerably by accounting for the proportions of different annual crops or crop classes like small grain or row crops. This was not possible due to limitations of the experimental studies. A large proportion (about 30% of plot years) only reported soil losses averaged over the total crop rotation. Important crops were underrated in the remaining experiments reporting individual crops (e.g., rape and potato had less than five plot years while they contribute 10.8 and 2.4% respectively to annual arable land; Destatis, 2002) and experiments reporting individual crops often had treatments (cultivation techniques, crop rotations) differing considerably from reality. Moreover, measurements of erosion in case of individual crops within a crop rotation do not take into account carry-over effects of previous crops, which can be large (e.g. Fiener and Auerswald, 2007).

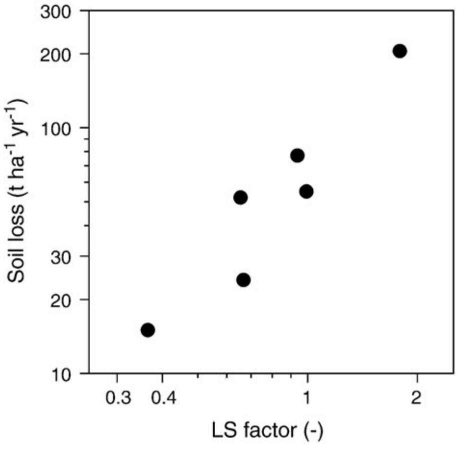

Fig. 5. Comparison between the predicted LS factor and long-term mean annual soil loss of hop gardens; raw data from Table 5; R factor is near identical for all sites 69 N h^{-1}; K factor varies between 0.32 and 0.45 t ha^{-1} yr^{-1} h N^{-1}; including the K factor slightly improves the prediction from $R^2=0.90$ to $R^2=0.96$; both axes are log scaled.

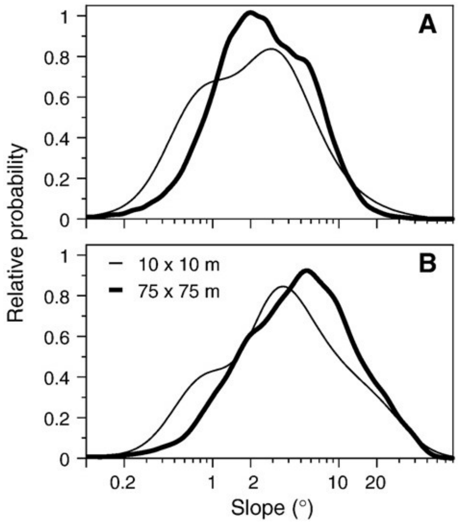

Fig. 6. Probability of slope within the Rur catchment (2354 km^2) depending on landuse and grid resolution; A: arable land, B: total land; shown as kernel density distribution; calculated after log transformation to account for the skewed distribution and then back transformed after kernel density estimation; to allow for comparison of differently sized data sets integral density was set equal; Silverman (1986).

The expected average soil loss from annual arable land, although based on a considerable number of plot years, is strongly influenced by results from one location. This location (Scheyern) contributed 123 yr to a total of 416.2 yr (Table 6). Unfortunately, all studies carried out at Scheyern examined annual arable landuses for which comparably little soil loss can be expected. One study examined only small grain, one study examined a full soil conservation system and the third examined organic farming with soil conservation, which also produces much lower soil loss than conventional farming (Auerswald et al., 2003). Hence, average soil loss at this location was only one fourth of the German overall average and a calculation without the data from this location would increase the German average by 37%. Nevertheless, we included all data in the German average because the

Table 6

Soil erosion from annual crops standardized to 5.1° slope gradient, 200 m slope length and average erosivity for studies at the Scheyern experimental farm as compared to German averages; all data weighted for plot years.

No.	Location	Landuse	Plot years	Erosion (t ha^{-1} yr^{-1})	Study
1	Scheyern	Conventional farming, Conventional tillage, small grain	23	3.6	Schimmack et al., 2002
2	Scheyern	Conventional farming, Full soil conservation, mixed rotation	60	2.6	Auerswald et al., 2003
3	Scheyern	Organic farming With soil conservation, mixed rotation	40	0.1	Auerswald et al., 2003
4	Scheyern	Arable, total	123	2.0	This study
5	Germany	Arable, total	416.2	15.5	This study
6	Germany	Arable, without Scheyern	293.2	20.7	This study

data from Scheyern are more realistic than most data from other studies concerning other aspects (long-term, whole-year measurements on field scale) and also all other studies must be regarded unrealistic in some aspects of their plot treatments (plots are often too small as compared to fields; they do not allow to use heavy machinery, etc.). We conclude that in spite of a considerable number of studies on soil erosion there is still little experimental evidence on soil loss under realistic landuse conditions. We may further conclude that arable soil loss could be considerably lowered by soil conservation systems. If we set the German average without Scheyern as 100%, we could expect to lower soil loss by sheet and rill erosion to 17% by (unrealistically) converting all fields to small grain, to 12% by applying a full conservation system, which is more realistic, or to 1% by converting all into an organic farming system, which especially considers soil erosion in its farming decisions as it was the case at Scheyern (Auerswald et al., 2000).

The combination of 27 studies and the standardization by modelling levelled out some of the major errors of different studies. Nevertheless, many errors still exist. While some of them only contribute to the scatter, others lead to a bias, which will not level out even by including many studies. One of them can be predominantly identified, which results from publication policies. Several measuring campaigns are known to us, which were carried out but never published because (almost) no erosion occurred during the study period. Although these measurements may be the most accurate, they lead to no insight into processes or treatments and hence could not be published. Published data thus overrate erosion rates.

While the errors of the different studies are still contained in our meta-analysis, an error can result from the meta-analysis itself in the case of erosion. Long-term measurements can be regarded best because they account better for years of especially low or high erosion rates but this implies that some of the data contributing to them are rather old. Combining these data in a meta-analysis causes an additional delay. Some of the erosion events contributing to the measured soil loss of hops already occurred in the first half of the 20th century (Table 3). The same is true for the long-term data by Kuron et al. (1956). Agricultural and forestry practices faced dramatic changes in many aspects during the last decades. Moreover, climate change within the last century may have increased rain erosivity in some areas of Germany. It is difficult to assess whether these old data still reflect erosion under current soil use and climatic conditions.

Hence, despite the large number of studies and plot years included in this meta-analysis and the reasonable quality of spatial input data, the calculated erosion rates still have to be regarded a rough estimate.

5. Conclusions

There are a considerable number of studies reporting measured sheet and rill erosion under natural rainfall in Germany (in total 1076 plot years). However, these studies cover too short time scales to account for the large temporal variability of erosion events and hence it is impossible to derive statistically sound average erosion rates. Furthermore, a considerable number of these studies were carried out on sites that are too steep and do not represent average erosivity compared to the German average of the respective landuse. Finally arable plots were largely overrated in these studies as compared to the contribution of annual arable land to rural land in Germany. The first deficiency could be overcome by combining all studies. The second deficiency was overcome by adjusting the measured soil losses according to the slope gradients and the erosivity of a certain landuse as derived from spatially distributed national raster data sets (digital elevation model, landuse classification and erosivity map) in a 75 m resolution. The third deficiency was overcome by adjusting the measured soil erosion data according to agricultural statistics of landuse.

Soil loss by sheet and rill erosion averaged over total rural land is 2.7 t ha^{-1} yr^{-1}, where annual arable crops contribute by far the largest part (90%). Their average soil loss amounts to 5.7 t ha^{-1} yr^{-1} but is about twice as high if the mostly flat areas of the North German Lowlands are not taken into account. Hops, despite their negligible contribution to landuse (0.06%), still contribute 1.0% to total soil loss due to the extraordinary large erosion rates measured for this crop. These averages still have to be regarded uncertain despite the large number of studies. These uncertainties can only be overcome by better experimental studies, involving realistic, long-term, and field-scaled scenarios.

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References

Ammer, U., Breitsameter, J., Zander, J., 1995. Der Beitrag des Bergwaldes zum Schutz gegen Oberflächenabfluß und Bodenabtrag. Forstwissenschaftliches Centralblatt 114, 232–249.

Aniol, R., 1975. Flächenausdehnung kurzer Starkregen in einem dichten Regenschreibernetz. Interpraevent 1975, 149–158.

Auerswald, K., 1993. Bodeneigenschaften und Bodenerosion — Wirkungswege bei unterschiedlichen Betrachtungsmaßstäben. Borntraeger, Berlin.

Auerswald, K., Kutilek, M., 1998. A European view to the protection of the soil resource. Soil & Tillage Research 46, 9–11.

Auerswald, K., Albrecht, H., Kainz, M., Pfadenhauer, J., 2000. Principles of sustainable land-use systems developed and evaluated by the Munich Research Alliance on Agro-ecosystems (FAM). Petermanns Geographische Mitteilungen 144, 16–25.

Auerswald, K., Kainz, M., Fiener, P., 2003. Erosion potential of organic versus conventional farming evaluated by USLE modelling of cropping statistics for agricultural districts in Bavaria. Soil Use and Management 19, 305–311.

Barkusky, D., 1990. Schutz vor Wassererosion im Silomais durch Zwischen-und Untersaat. Archiv für Acker-Pflanzenbau und Bodenkunde 6, 385–391.

Botschek, J., 1991. Bodenkundliche Detailkartierung erosionsgefährdeter Standorte in Nordrhein-Westfalen und Überprüfung der Bodenerodierbarkeit (K-Faktor). Hamburger Bodenkundliche Arbeiten, vol. 16. Hamburg.

Brandt, C.J., 1989. The size distribution of throughfall drops under vegetation canopies. Catena 16, 507–524.

Cerdan, O., Poesen, J., Govers, G., Saby, N., Le Bissonnais, Y., Gobin, A., Vacca, A., Quinton, J., Auerswald, K., Klik, A., Kwaad, F.F.P.M., Roxo, M.J., 2006. Sheet and rill erosion. In: Boardman, J., Poesen, J. (Eds.), Soil Erosion in Europe. Wiley, pp. 501–514.

De Alba, S., Lindstrom, M., Schumacher, T.E., Malo, D.D., 2004. Soil landscape evolution due to soil redistribution by tillage: a new conceptual model of soil catena evolution in agricultural landscapes. Catena 58, 77–100.

Destatis, 2002. http://www.destatis.de/basis/d/umw/ugrtab7.htm (Statistisches Bundesamt Deutschland; verified 28 May 2003).

Deumlich, D., Gödicke, K., 1989. Untersuchungen zu Schwellenwerten erosionsauslösender Niederschläge im Jungmöränengebiet der DDR. Archiv für Acker-Pflanzenbau und Bodenkunde 11, 709–716.

Deumlich, D., Frielinghaus, M., 1994. Methoden zur Erfassung der Wassererosion auf Ackerschlägen durch natürliche Niederschläge. Wasser und Boden 46 (12), 10–13.

Dikau, R., 1986. Experimentelle Untersuchungen zu Oberflächenabfluß und Bodenabtrag von Messparzellen und landwirtschaftlichen Nutzflächen. Heidelberger Geographische Arbeiten, vol. 81. Heidelberg.

Dubber, H.J., 1968. Untersuchungen über den Bodenabtrag auf Tonmergel-und Kalksteinverwitterungsböden der Schwäbischen Alb und ihres Vorlandes. Zeitschrift für Kulturtechnik und Flurbereinigung 9, 85–101.

ECC (European Communities-Commission), 1992. CORINE land cover project — technical guide. Publication of the European Commission, No. EUR 12585, Luxembourg.

Emde, K., 1992. Experimentelle Untersuchungen zu Oberflächenabfluß und Bodenaustrag in Verbindung mit Starkregen bei verschiedenen Bewirtschaftungssystemen in Weinbergsarealen des oberen Rheingaus. Geisenheimer Berichte. Gesellschaft zur Förderung der Forschungsanstalt Geisenheim, Geisenheim, vol. 12.

Emde, K., Friedrich, K., Löhnertz, O., 2005. Weinbergsböden und Bodenschutz in den Weinbaugebieten Rheingau und Mittelrhein. Mitteilungen Deutsche Bodenkundliche Gesellschaft 105, 115–122.

Felix, R., Johannes, B., 1993. Untersuchung der Beziehung zwischen Niederschlag, Oberflächenabfluß und Bodenerosion auf unterschiedlich genutzten Hochgebirgsstandorten. Forschungsbericht Nationalpark Berchtesgaden, Nationalparkverwaltung, Berchtesgaden.

Fiener, P., Auerswald, K., 2006. Seasonal variation of grassed waterway effectiveness in reducing runoff and sediment delivery from agricultural watersheds. Soil & Tillage Research, 87, 48–58.

Fiener, P., Auerswald, K., 2007. Rotation effects of potato, maize and winter wheat on soil erosion by water. Soil Science Society of America Journal. 71, 1919–1925.

Fiener, P., Auerswald, K., 2009. Farm-scale spatio-temporal variability of rainfall characteristics. Earth Surface Processes and Landforms. doi:10.1002/esp.1779.

Fleige, H., Horn, R., 2000. Field experiments on the effect of soil compaction on soil properties, runoff, interflow and erosion. Advances in Geoecology 32, 258–268.

Frielinghaus, M., 1998. Bodenschutzprobleme in Ostdeutschland. In: Richter, G. (Ed.), Bodenerosion — Analyse und Bilanz eines Umweltproblems. Wissenschaftliche Buchgesellschaft, Darmstadt, pp. 204–221.

Goeck, J., 1989. Untersuchungen zur Wassererosion im Silomaisanbau mit und ohne Untersaat (Weißklee) bei variierten Saatterminen unter Berücksichtigung der Ertragsleistung. Ph.D. thesis, Univ. Kiel, Kiel, Germany.

Goeck, J., Geisler, G., 1989. Erosion control in maize fields in Schleswig-Holstein (F.R.G.). Soil Technology Series 1, 83–92.

Guth, P.L., 2006. Geomorphometry from SRTM: comparison to NED. Photogrammetric Engineering & Remote Sensing 72, 269–277.

Jung, L., Brechtel, R., 1980. Messung von Oberflächenabfluß und Bodenabtrag auf verschiedenen Böden der BRD. Parey, Hamburg.

Knoll, G., Sieber, H., 1986. Die Hallertau. Frisinga Verlag, Freising, Germany.

Königer, S., Schwab, A., 2000. Application of a Geographical Information System (GIS) for the determination of soil erosion risk in Franconian vineyards, northwestern Bavaria, Germany. Congress on Regional Geological Cartography and Information Systems, Munich, vol. 3, pp. 155–159.

Königer, S., Schwab, A., 2002. Anwendung eines Geographischen Informationssystems (GIS) zur Planung verbesserter Bodenschutzmassnahmen im Weinbaugebiet Franken (NW-Bayern, Deutschland). Zeitschrift der Geologischen Wissenschaften 30, 351–364.

Kuron, H., Jung, L., Schreiber, H., 1956. Messungen von oberflächlichem Abfluß und Bodenabtrag auf verschiedenen Böden Deutschlands. Schriftenreihe des Kuratoriums für Kulturbauwesen, vol. 5. Wasser und Boden/Hamburg.

Lindstrom, M.J., Nelson, W.W., Schumacher, T.E., 1992. Quantifying tillage erosion rates due to moldboard plowing. Soil & Tillage Research 24, 243–255.

Martin, W., 1988. Die Erodierbarkeit von Böden unter simulierten und natürlichen Regen und ihre Abhängigkeit von Bodeneigenschaften. Ph.D. thesis, TU München, Freising-Weihenstephan.

McCool, D.K., Foster, G.R., Weesies, G.A., 1997. Slope length and steepness factors (LS). In: Renard, K.G., Foster, G.R., Weesies, G.A., McCool, D.K., Yoder, D.C. (Eds.), Predicting Soil Erosion by Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE). USDA-ARS, Washington, pp. 101–141.

Murphree, C.E., Mutchler, C.K., 1981. Verification of the slope factor in the universal soil loss equation for low slopes. Journal of Soil Water Conservation 36, 300–302.

Nearing, M.A., 1997. A single, continuous function for slope steepness influence on soil loss. Soil Sciences of America Journal 61, 917–919.

Oldeman, L.R., Hakkeling, R.T.A., Sombroek, W.G., 1991. World Map of the Status of Human-induced Soil Degradation. Global Assessment of Soil Degradation (2. Ed.). ISRIC and UNEP, Wageningen.

Poesen, J.W.A., Verstraeten, G., Soenens, R., Seynaeve, L., 2001. Soil losses due to harvesting of chicory roots and sugar beet: an underrated geomorphic process? Catena 43, 35–47.

Preuss, O., 1977. Über den Nährstoffab-und-austrag aus landwirtschaftlich genutzen Flächen — Dargestellt an einem definierten Wassereinzugsgebiet eines für die mitteldeutsche Gebirgslandschaft typischen Fließgewässers 3. Ordnung. Ph.D. thesis, Univ. Göttingen, Göttingen.

Rabus, B., Eineder, M., Roth, A., Bamler, R., 2003. The shuttle radar topography mission — a new class of digital elevation models acquired by spaceborne radar. ISPRS Journal of Photogrammetry and Remote Sensing 57, 241–262.

Richter, G., 1987. Investigation of soil erosion in central Europe. Seesoil 3, 14–27.

Richter, G., 1991. The soil erosion measurement station and its program. Forschungsstelle Bodenerosion 10, 97–108.

Rogler, H., 1981. Die Erosivität der Niederschläge in Bayern. Diplomarbeit, Lehrstuhl f. Bodenkunde, TU München, Weihenstephan.

Sauerborn, P., 1994. Die Erosivität der Niederschläge in Deutschland — Ein Beitrag zur quantitativen Prognose der Bodenerosion durch Wasser in Mitteleuropa. Bonner Bodenkundliche Abhandlungen, vol. 13. Bonn.

Saupe, G., 1990. Winterweizen — unterschätzte Erosionsgefahren? Feldwirtschaft 31, 367–368.

Saupe, G., 1992. Wirkung von Konturgrasstreifen zur Erosionsbekämpfung unter Praxisbedingungen. Zeitschrift für Kulturtechnik und Flurbereinigung 33, 150–162.

Schimmack, W., Auerswald, K., Bunzl, K., 2002. Estimation of soil erosion and deposition rates at an agricultural site in Bavaria, Germany, as derived from fallout radiocesium and plutonium as tracers. Naturwissenschaften 89, 43–46.

Schmidt, F., 1979. Die Abschätzung des Bodenabtrages in Hopfengärten mit Hilfe der Kupferbilanz. Ph.D. thesis, TU München, Freising-Weihenstephan.

Schwertmann, U., Schmidt, F., 1980. Estimation of long term soil loss using copper as a tracer. In: De Boodt, M., Gabriels, D. (Eds.), Assessment of Erosion. Wiley, London, pp. 203–206.

Schwertmann, U., Vogl, W., Kainz, M., 1987. Bodenerosion durch Wasser — Vorhersage des Bodenabtrags und Bewertung von Gegenmaßnahmen. Ulmer, Stuttgart.

Silverman, B.W., 1986. Density estimation for statistics and data analysis. Monographs on Statistics and Applied Probability. Chapman and Hall/CRC, London. 176 pp.

Steudle, G., 1997. Surveying and mapping in Germany. GIS Europe 6, 22–24.

Voss, W., 1978. Ermittlung der Nährstoffumlagerung durch Erosion und Charakterisierung der Erosionsfracht einiger Vorfluter in hessischen Mittelgebirgs-Kleinlandschaften. Ph.D. thesis, Univ. Gießen, Gießen.

Warren, S.D., Mitasova, H., Auerswald, K., Hohmann, M.G., 2004. An evaluation of methods to determine slope using digital elevation data. Catena 58, 215–233.

Wischmeier, W.H., 1960. Cropping-management factor evaluations for a universal soil-loss equation. Soil Science Society America Proceedings 24, 322–326.

Wischmeier, W.H., Smith, D.D., 1978. Predicting Rainfall Erosion Losses — A Guide to Conservation Planning. USDA Agricultural Handbook, vol. 537. U.S. Gov. Print Office, Washington, DC.