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REGIONAL INVENTORY APPROACH TO ESTIMATE METHANE EMISSIONS BASED ON SOIL-LAND USE CLASSES

With 3 figures, 2 tables and 1 appendix

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Zusammenfassung: Regionale Inventur zur Abschätzung der Methanflüsse auf Grundlage von Boden-Landnutzungs-Klassen
Da die Eingangsparameter von prozessbasierten Methan (CH_4)-Emissions-Modellen oft nicht in der benötigten räumlichen Auflösung zur Verfügung stehen, ist die Abschätzung der regionalen CH_4-Emission oft nicht möglich. Andererseits sind landesweite Treibhausgas-Inventur-Ansätze nicht in der Lage, Emissionen mit hinreichender räumlicher Auflösung darzustellen. Wir haben eine globale CH_4-Fluss-Datenbasis kompiliert und jeder Flussabschätzung eine Boden-Landnutzungs-Kombination zugewiesen. Mit Hilfe von Fernerkundungsdaten und eines Geographischen Informationssystems stellten wir eine Karte des württembergischen Allgäus her, die die Boden-Landnutzungs-Kombinationen der Region darstellt. Wir belegten jede Boden-Landnutzungs-Kombination mit dem der Einheit zugehörigen Median CH_4-Fluss aus der globalen Datenbasis. Unsere Abschätzung für die regionalen CH_4-Emissionen beträgt 5,6 kg C ha^{-1} a^{-1}. Der Vergleich der CH_4-Flüsse der globalen Datenbasis mit gemessenen regionalen Flüssen zeigte eine zwei- bis dreifache Überschätzung der CH_4-Flüsse durch die Datenbasis. Wir sind der Meinung, dass unsere Vorgehensweise eine plausible Abschätzung der CH_4-Flüsse auf regionalem Maßstab liefert und eine weitergehende Evaluierung in anderen Regionen durchgeführt werden sollte.

Summary: Regional estimations of methane (CH_4) emissions employing process-based models are often not possible due to a lack of input parameters at the required spatial resolution. On the other hand, national greenhouse gas inventories are not able to express emissions with sufficient spatial resolution. We assembled a global CH_4 flux database and assigned each flux estimate to a soil-land use combination. We applied the median CH_4 fluxes from these soil-land use combinations to a remote sensing and GIS generated soil and land use map of the Allgäu region in southwestern Germany. Our CH_4 emission estimate from the database for the region was 5.6 kg C ha^{-1} yr^{-1}. Comparison of CH_4 fluxes from the database with measured local fluxes resulted in a two- to threefold over-estimation by the database estimate. We conclude that our approach delivers a plausible estimate of CH_4 fluxes at the regional scale and should be further evaluated in other regions.

1 *Introduction*

Methane (CH_4) is one of the most important greenhouse gases. According to ALBRITTON et al. (2001), it contributes 20% of the radiative forcing to the atmosphere. LELIEVELD et al. (1998) estimate a global annual emission of 450±60 Tg CH_4. Due to a poor characterization of sources and sinks, the prediction of future atmospheric CH_4 concentrations remains problematic (ALBRITTON et al. 2001). As (wetland) soils may be most important CH_4 sources (FIEDLER a. SOMMER 2000), an improved knowledge of CH_4 emissions from soils is needed.

In some areas, this need for knowledge is due to insufficient spatial aggregation of existing flux estimates rather than too little flux measurements in the field. Spatial models or estimates of methane emissions require down-scaling or up-scaling procedures (VAN BODEGOM et al. 2002). These models are generally ecosystem-specific (VALENTINE et al. 1994; HUANG et al. 1998; WALTER a. HEIMANN 2001; VAN BODEGOM et al. 2001) or require complex input parameters (MATTHEWS et al. 2000) that are rarely known or available on a regional level. To our knowledge, spatial models that are able to approximate methane fluxes from a variety of ecosystems require parameters that are not documented for entire regions (apart from specially equipped research sites).

Nitrous oxide (N_2O) emissions have been spatially modeled using a "soil-land use system approach" on a regional scale by BARETH et al. (2001). This approach was inspired by the "ecosystem approach" by MATSON and VITOUSEK (1990), who used the "relationship among soil fertility, nitrogen cycling, and N_2O production to estimate N_2O flux from humid tropical forest". Since such relationships to methane fluxes are well established on the process scale (SEGERS 1998), it should be possible to generate a regional estimation of methane fluxes as well where a satisfactory database is available and soil processes can be linked to soil types. Such a link has been proposed by FIEDLER and SOMMER (2000), who pointed out that soil morphological properties may be used to infer CH_4 emission characteristics.

Since 1992, interdisciplinary research projects at the University of Hohenheim in Stuttgart, Germany, have carried out CH_4 flux measurements on different soils under different land use in the "württembergisches Allgäu" region (SW Germany). These projects have resulted in detailed information on magnitude and controls of methane fluxes (KLEBER 1997; KLEBER et al. 1998; GLATZEL 1999; FIEDLER a. SOMMER 2000; SOMMER a. FIEDLER 2002; GLATZEL a. STAHR 2001, 2002). Additionally, a comprehensive GIS was implemented for this region on the basis of available geodata (BARETH 2000). The objective of this contribution is to estimate CH_4 fluxes from soils (emissions and uptake) based on the soil-land use system approach for the entire region "württembergisches Allgäu" and to evaluate whether this approach is able to provide plausible flux estimates for the individual landscape units within the region.

2 Materials and Methods

2.1 Study region

The "württembergisches Allgäu" is located around 150 km westsouthwest of Munich (Fig. 1). It belongs to the humid and cool areas in Southern Germany. The entire study region covers around 775 km^2. Annual rainfall is 1,200 mm in the northwest and increases to 1,800 mm towards the Alps in the southeast (KLEIN a. MENZ 2003). Mean monthly precipitation is distributed almost evenly throughout the year. Annual groundwater discharge amounts to 500–1,000 mm. Periods of negative water balance are scarce. Mean annual temperature is between 6 and 7 °C (SCHIRMER 1978). In winter, the average temperature falls below 0 °C for 1 to 4 months, but due to snow cover soils seldom freeze (STAHR 1994).

The topography of the study region with rolling hills and closed depressions is a result of the processes of the last glacial period. Soil development did not begin until the retreat of the Rhine glacier towards the end of the Würm glaciation (equivalent to the Wisconsian in North America) around 10,000 years BP.

The cool and humid climate with a vegetation period of approximately 205 days favours dairy production with intensive grassland as dominant land use. The most widespread plant community is a perennial ryegrass sward (*Lolium perenne*). Land use intensity is characterized by 3–5 cuts a year and up to five slurry applications. Meadow utilization dominates over pasture (KLEBER 1997). Average animal stocking is 1.9 livestock units ha^{-1} (HORLACHER et al. 1997). Mean atmospheric N-deposition for non-forest areas is 10 kg ha^{-1}yr^{-1} (HORLACHER et al. 1997).

Soils on the glacial sediments decalcify and pass the Orthent stage (following U.S. DEPARTMENT OF AGRICULTURE 1998) quickly. Clay illuviation (Hapludalfs) is often followed by stagnating conditions (Aqualf). Under natural circumstances, only these last two soil types are present. The Orthents are common in areas with extensive soil erosion. Plateaux are covered by Aqualfs, the eroded topslopes feature Orthents, on the colluviated footslopes, Eutrochrepts have developed and in the depressions Aquepts and Hemists prevail. In the depressions of the "württembergisches Allgäu", fens and bogs dominate (STAHR 1994).

2.2 Databases for the region and temperate zone

We conducted a literature review (34 published references) on methane fluxes from soils in temperate regions (Appendix). Thus, we excluded data from arid continental, boreal, subpolar, polar, subtropical, and tropical ecosystems. However, we did include data from oceanic and cool temperate continental climates. Since our study region is located in Western Europe and has

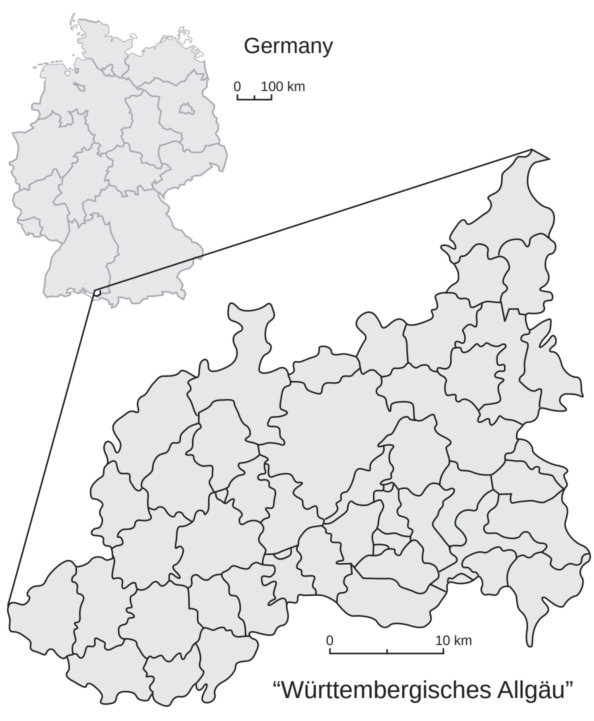

Fig. 1: Location of the research region "württembergisches Allgäu"

Das Untersuchungsgebiet „württembergisches Allgäu" an oceanic climate, we took care to include as many studies as possible from oceanic temperate climates, so that the review on these ecosystems might be more complete. We also limited our review to field studies that lasted at least one season.

We compiled our regional database from published methane flux data that has been gained since 1995 in the study region by KLEBER (1997), FIEDLER and SOMMER (2000), GLATZEL and STAHR (2001, 2002). The authors determined the methane flux at 11 locations representing relevant soil and land use units within the study region (Tab. 1).

2.3 Generation of spatial data

The spatial soil and land use databases are generated only from available geodata. The spatial soil information is created by a disaggregation of the soil map 1:200,000 using a relief analysis of a digital elevation model (DEM) in a 50 m grid. The relief analysis is done with the System for Automated Relief Analysis (SARA) which has been developed at the Institute of Geography at the University of Göttingen (KÖTHE a. LEHMEIER 1996a, b, c). In a second step, the relief analysis is overlayed with the soil survey map of Baden-Württemberg which is available in the scale 1:200,000. This digital soil map provides very detailed descriptions of the soil mapping units and describes the soil types of each soil mapping unit in dependency on relief units. This knowledge about spatial soil type distribution is used to disaggregate the spatial soil mapping units. Consequently, an overlay of the relief analysis with the soil map 1:200,000 by GIS routines enables the knowledge based disaggregation of the soil units which is described in detail by BARETH (2001a).

The quality of the available spatial land use information is poor. Therefore, a method to enhance the quality of the official spatial land use information has been introduced by BARETH (2001b). The results of a supervised land use classification of an IRS–1C (Indian Remote Sensing Satellite) scene were incorporated into the official topographical cartographical information system called ATKIS (Amtliches Topographisch-Kartographisches Informationssystem). Only spatial information with low quality was replaced by the results of the satellite image analysis.

According to the soil-land use system approach (BARETH et al. 2001), a GIS-based overlay of the spatial soil and land use information enables the identification of the various soil-land use-systems. These soil-land use-systems are the spatial basis for the regional modeling.

Our database assigns a land use type and soil type to each point in the research area (Tab. 2). The land use types used in this study are forest, grassland, arable land, and wetland. The soil units within the grassland land use category are illustrated in figure 2. The four land use units cover 99.6% of the total land use in the study region "württembergisches Allgäu". The 0.4% that are not accounted for are special land use systems, e.g. apple orchards. The soil types are Spodosol, non-illuvial soil, illuvial soil, hydromorphic soil, fen/swamp, peat bog, and peaty mineral soil. Thus, there are 4 x 7 = 28 possible soil-land use combinations. In reality,

Table 1: Annual methane fluxes from 11 representative soil-land use units in the study region "württembergisches Allgäu"

Jährliche Methanflüsse von 11 repräsentativen Boden-Landnutzungs-Einheiten im Untersuchungsgebiet „württembergisches Allgäu"

Location	Soil type	Land use type	CH_4-C flux kg ha^{-1} yr^{-1}	Reference
Siggen	Typic Hydraquent	Wetland	1665	KLEBER et al. (1998)
Siggen	Typic Hydraquent	Wetland	5	
Aichstetten	Aeric Endoaquept	Grassland	4	FIEDLER a. SOMMER (2000)
Aichstetten	Mollic Endoaquept	Grassland	8	
Wangen	Limnic Haplohemist	Wetland	93	
Wangen	Limnic Haplohemist	Grassland	12	
Artisberg	Fluvaquentic Humaquept	Wetland	414	
Artisberg	Typic Humaquept	Wetland	174	
Siggen	Oxyaquic Eutrochrept	Grassland	1	GLATZEL a. STAHR (2001)
Siggen	Oxyaquic Eutrochrept	Grassland	2	
Siggen	Typic Hydraquent	Wetland	17	GLATZEL a. STAHR (2002)

some soil and land use-combinations (as Spodosol in grassland or peat bog in forest) did not occur, so merging of the two layers yielded 16 of the 28 theoretically possible soil type-land use type-combinations. In one case (grassland/illuvial soil), a soil-land use-combination that exists in the research region, was not represented by the database. In this case, we chose the mean between the grassland/non-illuvial soil and grassland/hydromorphic soil units, assuming that an illuvial soil experiences water logging more often than a non illuvial soil, but less often than a hydromorphic soil, thus emitting half as much methane as a hydromorphic soil.

The classification of all soils in the region into just seven soil units is due to two limitations: the limited number of studies that were fit for our database called for few broad soil units rather a large number of soil units that soil classifications offer on the top classification level. Also, the sometimes imprecise description of soil types in the database (for example "sandy soil") does not allow a designation according to major soil classifications. Also, it is sometimes difficult to translate soil types from different soil classifications (FAO 1998; U.S. DEPARTMENT OF AGRICULTURE 1998) into a common system. Since methane emissions rise with the degree of wetness, our classification (i) is focused on the degree of soil wetness and (ii) has a higher resolution in wetland soils.

Every long-term methane flux estimate from the database (Appendix) was assigned to a soil type land use type combination, yielding 117 long-term methane flux estimates. These estimates were grouped according to the soil type-land use type-combination they represent. We calculated the median long-term flux estimate within each land use type-soil type combination as representative value. The land use type-soil type combination with the most estimates (27) was forest/non-illuvial soil.

The flux estimates from the database were applied to the 16 soil-land use-units and the estimate for each unit was multiplied with its spatial extent.

2.4 Evaluation

We compared the methane flux estimate from the global database with the large regional long-term methane flux database in five of the 16 soil-land use units. We expressed the uncertainty of our estimate in percent of the value that has been measured with the regional database. Also, we tested the sensitivity of the estimate on the number of methane flux estimates in the global database (sample size, *n*) by calculating median CH_4 flux in the global database as a function of *n*.

3 Results and discussion

3.1 Rationale

Our regional estimation is based on the idea that soil morphological properties, as expressed by soil types and the type of land use, are important determinants of long-term methane efflux. The link between hydromorphic properties and long-term methane emissions has been demonstrated by FIEDLER and SOMMER (2000) and SOMMER et al. (2004). FIEDLER and SOMMER (2000) stress the importance of selected unit area emissions for any extrapolation.

The land classification into the units forest, grassland, arable land, and wetland is consistent with the land use units defined in the IPCC's recent land use, land use change, and forestry report (WATSON et al. 2000). This simple classification allows the detection of the land-use units with the spatial land use database. Any agricultural land use ruled out the designation as wetland, thus all wetlands in this study are natural or restored. Open water bodies were excluded from our study.

3.2 Soil types and land use units

The unit "Spodosols" is restricted to Spodosols/Podzols without hydromorphic properties that can be inferred from the name (as Aquod). The unit "non-illuvial soils" encompasses all soil types where no hydromorphic properties can be inferred from their designation and illuviation is not strong enough to justify their designation as an clay-illuviated soil at the highest classification level (as Alfisol or Alisol). Thus, this unit contains Cambisols, Inceptisols, Andisols, Entisols, and soils which are not classified according to a common soil classification, but described as being "loamy", "sandy", "clayey", "sandy loam", "acid brown soils" or "brown forest soils". The unit "illuvial soils" applies to all soils that are designated as clay-illuviated on the highest classification level (as Alfisol or Alisol). This unit was classified separately as a clay illuviated horizon may impede drainage and enhance methane emissions. The unit "hydromorphic soils" contains all mineral soils with hydromorphic properties that can be inferred from their designation, but with no designation that suggests the presence of a peaty topsoil (as in "Peaty Podzol"). The organic soils are separated into "fens/swamps", "peat bogs" and "peaty mineral soil".

3.3 Database methane fluxes

The highest CH_4 uptake (median 4 to 5 kg CH_4-C ha^{-1} yr^{-1}) was found in forests on non-illuvial soils and

Spodosols. All other land use-soil units had a median uptake of <1 kg CH_4-C ha^{-1} yr^{-1} (Tab. 2). No net CH_4 emissions were detected in forests and arable land (Fig. 3). As far as forests are concerned, this is probably due to a lack of data on peat bogs in our database. To our knowledge, such data exists only from boreal, but not from temperate ecosystems. In arable land, organic soils had been drained, so the aerobic topsoil prevented net CH_4 release. Unfortunately, the unit arable land on (drained) peat bog is based on one study only (Glenn et al. 1993). Interestingly, the forests took up methane even when located on hydromorphic soils.

Grassland ecosystems on peat bogs did not release CH_4, but on fen/swamp, they were strong CH_4 sources (59 kg CH_4-C ha^{-1} yr^{-1}) in our database. Peat bogs and fens/swamps in the wetland land use unit emitted less CH_4 compared to peat bogs in grassland (Fig. 3). This underlines the role of fertilization, which may provide substrate for methanogens in drained peat bogs used as grasslands. The highest CH_4 release in our database (137 kg C ha^{-1} yr^{-1}) occurred in peaty mineral soils where colluvial deposits lie on top of peat deposits in the riparian area of kettle holes (Fig. 3). In summary, our database showed that forests and arable land take up CH_4 and peaty mineral soils, wetlands as well as some grasslands are the strongest CH_4 sources.

3.4 Regional methane fluxes

The regional database (Tab. 1) illustrates the wide range of CH_4 fluxes that occur within the research region. None of the 11 sites was a CH_4 sink. The highest flux estimate (1,665 kg CH_4-C ha^{-1} yr^{-1}; Kleber et al. 1998) was gathered in a riparian area with colluvial deposits, a few meters from the site where the estimate a few years later was two orders of magnitude (17 kg

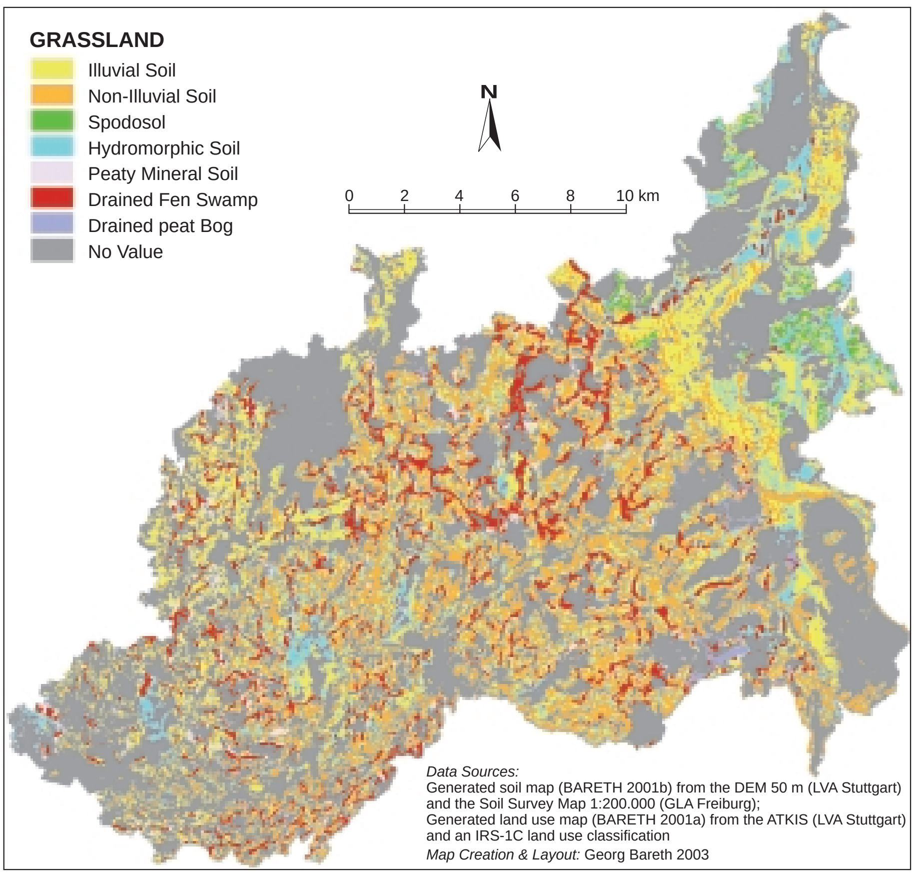

Fig. 2: Soil units within the land use type grassland in the research region "württembergisches Allgäu"

Bodeneinheiten innerhalb des Landnutzungstyps Grünland im Untersuchungsgebiet „württembergisches Allgäu"

Table 2: Methane flux estimates from the global database and regional measurements in the soil-land use units and their spatial extent for the flux estimation in the study region "württembergisches Allgäu"

Methanflussabschätzungen auf Grundlage der globalen Datenbasis und regionalen Messungen in Boden-Landnutzungs-Einheiten und ihre räumliche Ausdehnung für die Flussabschätzung im Untersuchungsgebiet „württembergisches Allgäu"

Land use unit	Soil unit	Area	CH_4-C flux	
			Database median	Regional estimate
		ha	kg ha^{-1} yr^{-1}	
Forest	Spodosol	960	–4	–
	Non-illuvial	7777	–5	–
	Illuvial	9750	0	–
	Hydromorphic	10132	0	–
Grassland	Peat bog	448	0	–
	Fen/swamp	7215	59	12
	Non-illuvial	15333	0	2
	Illuvial	13494	0	–
	Hydromorphic	12056	0	4
Arable land	Peat bog	11	0	–
	Non-illuvial	687	0	–
	Illuvial	1745	0	–
	Hydromorphic	344	0	–
Wetland	Peat bog	329	56	–
	Fen/swamp	495	32	93
	Peaty Mineral Soil	189	137	118

CH_4-C ha^{-1} yr^{-1}; GLATZEL a. STAHR 2002) smaller. High CH_4 efflux was observed in wetlands on peaty mineral soil and in fens/swamps. Except for a site on drained fen/swamp, CH_4 emissions in grassland were <9 kg CH_4-C ha^{-1} yr^{-1}. The two sites in grassland with non-illuvial soil differed in fertilization (one was unfertilized and the other one fertilized with >200 kg N ha^{-1} yr^{-1}, but their CH_4 efflux was approximately the same (1.2 vs. 1.8 kg CH_4-C ha^{-1} yr^{-1}; GLATZEL a. STAHR 2001).

3.5 Model evaluation

The regional CH_4 database (Tab. 1) is able to assess the adequacy of our global database for five of the 16 soil-land use units. Thus, we were able to evaluate the estimate for 43.6% of the modeled area. Six of the 11 locations where CH_4 flux in the region has been determined were grouped in the "wetland fen/swamp" and two soils belong to the "grassland on non-illuvial soils" unit. The three other units that could be used for the evaluation of the estimate depended on a single site. Three of the five soil-land use units that were used for evaluation were located on grassland, and the other two on wetland (Tab. 2). Thus, the forest and arable land units could not be evaluated. Forests and arable land cover 35.3 and 3.4% of the modeled area, respectively, and, according to the global database, do not contribute to CH_4 emissions. Therefore, we are able to evaluate the quality of the estimate for the most important land use type, covering 60% of the area (grassland) and emitting >90% of the CH_4.

The most important land cover-soil unit in our estimate is grassland on fen/swamp. Although it covers merely 8.9% of the area in the estimate, it emits 92.6% of the CH_4. As the global database supplies five sites from two studies in Germany and the Netherlands (FLESSA et al. 1998; VAN DEN POL-VAN DASSELAAR et al. 1999), we have confidence in the (high) mean flux of 59 kg CH_4 ha^{-1} yr^{-1}. Unfortunately, only one study from the research region can be used to evaluate the estimate. The CH_4 flux for this land cover-soil unit from the region amounts to 21% of the estimate from the global database and the value for the entire region depends strongly on this land cover-soil unit. Considering the high spatial and interannual variability of CH_4 fluxes, attaining the correct order of magnitude confirms the suitability of our approach.

The "grassland on non-illuvial soils" covers 18.9% of the area in the estimate and makes up 7.9% of the CH_4

sink. Our confidence in the global database estimate is high, as 26 sites from Denmark, Germany, Norway, and the USA could be pooled to generate the estimate and the range of CH_4 fluxes is small (Fig. 3). The methane flux at the two sites that are used to evaluate the estimate is beyond its range. This could be due to the colluvial origin of the soils: the soils in the region that represent "non-illuvial soils", consist of a layer rich in silt above loamy-textured material (GLATZEL a. STAHR 2001). This stratification sometimes impedes drainage and creates anaerobic conditions, facilitating CH_4 emission. Due to the small magnitude of CH_4 fluxes in this soil-land use unit, this shortcoming has no large influence on the regional net CH_4 emissions.

Grassland on hydromorphic soils covers 14.9% of the area in the estimate. According to the global database, which is made up of measurements from Denmark and Germany, this unit is CH_4-neutral. Our single site in this soil-land use unit also emits more CH_4 than the global estimate. The average flux of 4 kg CH_4 ha^{-1} yr^{-1} is well within the range of fluxes that is defined in the global estimate, but as the CH_4 fluxes in the global estimate are skewed towards small emissions, our regional estimate appears elevated.

In the research region, wetlands cover only 1.2% of the area and CH_4 fluxes in wetlands are extremely variable (Tab. 2). Therefore, the comparison of global database CH_4 emission estimates with measured fluxes in this unit assesses the suitability of our approach in locations with extreme spatial heterogeneity. The global database for fens/swamps in wetlands consists of seven datasets with a wide range and a median of 32 kg CH_4-C ha^{-1} yr^{-1}. This value is one third of our regional dataset, which has been taken at seven sites. Despite its small extent (0.2% of the research region), the small soil-land use unit "peaty mineral soil" in wetlands contributes 5.8% of the total CH_4 emission within the research region. The large dataset from the region fea-

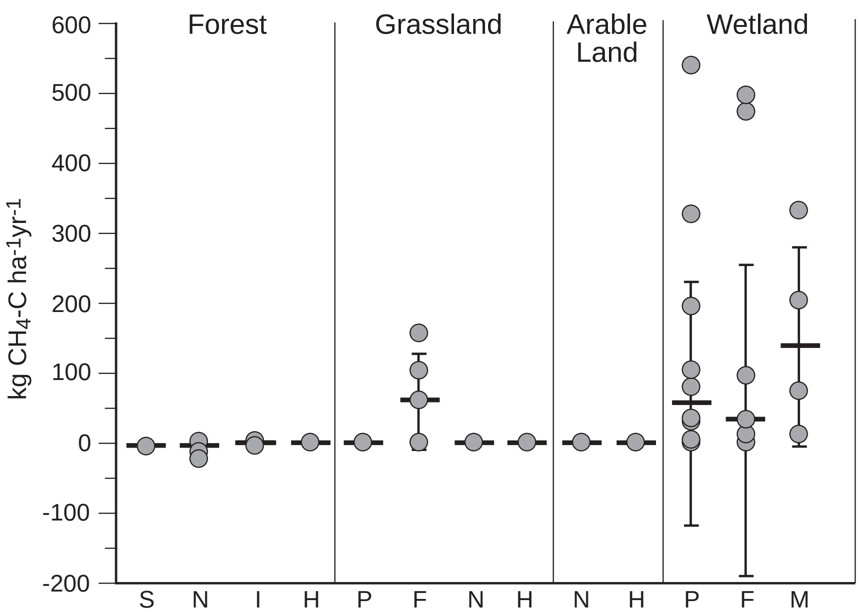

Fig. 3: Database methane fluxes in the forest, grassland, arable land, and wetland land use units and different soil units. Soil units are abbreviated as follows: S: Spodosol, N: Non-illuvial soil, I: Illuvial soil, H: Hydromorphic soil, P: Peat bog, F: Fen/Swamp, M: Peaty mineral soil. Dots indicate individual data points, bars median values for each soil-land use units and error bars standard deviations of data points within soil-land use units. The two soil-land use units featuring only one data point are not shown.

Methanflüsse der Datenbasis in den Landnutzungsklassen Wald, Grünland, Ackerland und Feuchtgebiet und verschiedenen Bodeneinheiten. Die Bodeneinheiten sind wie folgt abgekürzt: S: Podsol, N: Schwach entwickelte Böden ohne Tonverlagerung, I: Stärker entwickelte Böden mit Tonverlagerung, H: Hydromorphe Böden, P: Hochmoorböden, F: Niedermoorböden, M: Anmoorige Böden. Punkte stellen einzelne Datenpunkte und Balken Mediane innerhalb der Boden-Landnutzungsklasse dar. Die beiden Boden-Landnutzungsklassen mit nur einem Datenpunkt sind nicht dargestellt.

tures CH_4 fluxes that are very close to the CH_4 fluxes that have been found by MERBACH et al. (1996) in northeast Germany. This is due to the good agreement between the morphological and ecological characteristics of colluvial soils covering peaty deposits in the research area and the location where data for the evaluation was measured. The colluvial origin of many riparian (thus often "peaty mineral") soils in the research region and its significance for regional and possibly also global CH_4 fluxes has recently been described by SOMMER et al. (2004).

According to our global database, the research region Württemberg Allgäu emits 443 t CH_4-C yr^{-1}, which is in average 5.6 kg CH_4-C ha^{-1}. Within the five soil-land use units where an evaluation was possible, our estimate by the global database is 14.0 kg CH_4-C ha^{-1} and the regional examinations yield 5.1 kg CH_4-C ha^{-1}, which is 37% of the estimate. Thus, for the region, our approach is able to generate data at the correct order of magnitude, but some individual sites may be mis-estimated due to small datasets and the inability of a coarse soil classification to capture the ecological characteristics of some soil units.

The largest deviation between the values generated from the global database and the regional estimates occurred when the number of values from the global database was small. Thus we assumed that increasing the sample size (n) within soil-land use units in the global database stabilizes the median CH_4 emission. We tested this assumption for the 26 CH_4 flux estimates making up the global dataset for grassland on non-illuvial soils by randomly ordering the 26 estimates and calculating the median CH_4 emission for the first two estimates and then adding an additional estimate until the mean CH_4 emission for all 26 estimates was calculated. The median changes strongly until n is 7. For n>18, the median hardly shifts until n=26. This observation illustrates the necessity for a larger number of observations in key soil-land use units where our sample size was small.

3.6 Limitations and outlook

The approach chosen in this contribution intends to close the gap between process-based models and global models with a grid size that is larger than our entire research region (BATJES a. BRIDGES 1994). For regional modeling of greenhouse gas emissions with process-based agro-ecosystem models, the sensitive input parameters like soil organic matter content have to be estimated or derived from strongly aggregated sources e.g. small scale soil maps (LI et al. 2001; MATTHEWS et al. 2000). This raises the question whether knowledge based models of regional CH_4 emissions for different soil-land use-systems should be preferred, taking into account the diverse mosaic of landscape units, because the aggregation takes place on the result level and not on the input data level and is consequently more visible. The input parameters that are required for process-based models are generally not available for entire regions. For example, the simulation of NO and N_2O emissions in the denitrification and decomposition (DNDC) model that has been developed and adapted for modeling trace gas emissions by LI (2000) requires detailed information on climate (daily mean temperature, daily precipitation), soil properties (soil texture, soil porosity, soil moisture, soil temperature, clay content), and agricultural management (crop, date of tillage, fertilization). In order to model these parameters for regions, it is necessary to resort to information which is available for the entire region; for example soil maps or land use maps or to apply empirical equations (BUTTERBACH-BAHL et al. 2001).

For large regions, inventories might be the method of choice: The IPCC approach for modeling N_2O emissions, which aggregates even more strongly than our approach, yields the same results as the process-based mode by LI (2000) on the national inventory scale.

4 Conclusions

In summary, the soil-land use approach is able to generate CH_4 flux estimates that are within the correct order of magnitude. The performance of the approach for most of the soil-land use units is acceptable. A larger database that enables a more detailed selection of soil-land use units should describe the CH_4 flux more closely and yield better CH_4 flux estimates for these soil-land use units. Also, the application of the soil-land use approach at other environmental research sites with large local methane flux databases and the comparison with process-based models on selected soil-land use units should be the next steps in further evaluating its suitability.

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Appendix Part 1

Soil and land use unit	Soil type	Vegetation	CH_4-C flux	Reference
			kg ha^{-1} yr^{-1}	
FOREST				
Spodosol				
Woods Lake, NY USA	Typic to Lithic Haplorthod	Beech/Maple/Birch/Spruce	–1.64	1)
Petersham, MA USA	Entic Haplorthod	Red Pine	–9.64	2)
		Mixed deciduous	–10.51	
NW PA USA	Alfisol	Black Cherry, Sugar Maple	–6.68	3)
S. Scotland, GB	Peaty podzol	High altitude forest	0.53	4)
Copenhagen, Denmark	Orthod	Spruce (30 yrs. old)	–0.91	5)
Non-illuvial soil				
Hubbard Brook, NH USA	Sandy-loam	Mixed deciduous	0.04	6)
Durham, NH USA	Inceptisol, loamy sand	Mixed deciduous	–4.52	7)
S. Scotland, GB	Brown forest soil	Low altitude forest	0.98	4)
Gullane, GB	Brown forest soil	Mixed deciduous	–6.82	8)
Strødam, Denmark	Loamy sand	Spruce	–2.55	9)
Solling, Germany	Dystric Cambisol	Spruce	–0.55	10)
Solling, Germany	Dystric Cambisol	Beech	–0.08	
Spanbeck, Germany	Dystric Cambisol	Spruce	–0.23	
Göttinger Wald, Germany	Rendzic Leptosol/			
	Eutric Cambisol	Beech	–1.86	
Sandhausen, Germany	sandy	Beech/Spruce	–9.53	11)
	loamy	Beech/Oak/Maple	–2.33	
	clayey	Mixed deciduous	–2.78	
Nußloch, Germany	sandy	Beech/Spruce	–9.45	
	clayey	Spruce	–0.68	
Villingen, Germany	Acid brown soil	Picea abies, Abies alba, Pinus sylvestris	–5.40	12)
		Picea abies, Abies alba, Pinus sylvestris	–5.54	
Wildmooswald, Germany	Endoskeletic Cambisol	Spruce	–3.1	13)
	Chromic Cambisol	Spruce	–4.5	
Schottenwald, Austria	Dystric Cambisol	Beech	–0.76	14)
Klausenleopoldsdorf, Austria	Dystric Cambisol	Beech	–1.33	
Kitaibaraki, Japan	Andisol	Oak	–6.85	15)
	Inceptisol	Beech	–13.42	
	Andisol	Cedar	–13.42	
Hitachi Ohta, Japan	Inceptisol	Cypress & Cedar	–4.93	
		Oak	–9.03	
Tsukuba, Japan	Inceptisol	Cedar	–4.93	
Kaba, Japan	Inceptisol	Deciduous	–20.81	
Illuvial soil				
Vicinity of Copenhagen, Denmark	Udalf	Spruce (26 yrs. old)	–0.37	5)
Lappwald, Germany	Eutric Vertisol	Beech, Oak	–1.01	10)
Harste, Germany	Haplic Lixisol	Beech	–0.56	
Klausenleopoldsdorf, Austria	Stagnic Alisol	Beech	2.02	14)
Hydromorphic soil				
Lappwald, Germany	Dystric Gleysol	Spruce	–0.14	10)
Canstein, Germany	Gleyic Cambisol	Poplar (5 yrs. old)	–0.30	16)
		Poplar (5 yrs. old)	–0.36	
		Poplar (10 yrs. old)	–0.28	
		Oak (32 yrs. old)	–0.14	
Wildmooswald, Germany	Humic Gleysol	Spruce	–0.4	13)
	Histic Gleysol	Spruce	1,2	
			18,6	

to be continued on page 10

Appendix Part 2

Soil and land use unit	Soil type	Vegetation	CH_4-C flux kg ha^{-1} yr^{-1}	Reference
GRASSLAND				
Peat bog				
Zegveld, Netherlands	Terric histosol,	Grassland (mainly ryegrass)	–0.06	
			–0.29	
			–0.17	
			0.05	
			–0.22	
			–0.20	17)
Fen/swamp				
Drie Berke Zudden, Netherlands	Fen	Grassland, Rushes, Sedges, mown 1–2 x yr^{-1}	59.25	17)
Koole, Netherlands	Fen	Grassland, Rushes, Sedges, mown 1–2 x yr^{-1}	99.75	
Brampjesgat, Netherlands	Fen	Grassland, Rushes, Sedges, mown 1–2 x yr^{-1}	153.00	
Donaumoos, Germany	Drained fen	2 cuts-meadow	–1.04	18)
		3 cuts-meadow	–0.83	
Non-illuvial soil				
Wyoming, USA	Dystric cryochrept	Wet subalpine meadow	–1.09	19)
Surnadal, Norway	Typic Udorthent	Timothy, Clover	–0.27	
			–0.28	
			–0.40	
			–0.40	
			–0.59	
			–0.61	20)
Surnadal, Norway	Typic Udorthent	Timothy, Clover	–0.08	
			–0.14	
			–0.14	
			–0.18	
			–0.20	
			–0.27	
			–0.29	
			–0.34	
			–0. 36	
Surnadal, Norway	Typic Udorthent	Timothy, Clover	–0.18	
			–0.20	
			–0.28	
			–0.32	
Surnadal, Norway	Typic Udorthent	Timothy, Clover	–0.6	
			–0.14	
			–0.24	
			–0.41	
Copenhagen, Denmark	Psamment	Abandoned Grasses, Broom Shrub	–0.80	5)
Scheyern, Germany	Dystric Eutrochrept	Pasture	0.08	21)
Hydromorphic soil				
Copenhagen, Denmark	Aquent	Grasses, Glass Wort	0.22	5)
Klarer Pfuhl, Germany	Gleyic Luvisol	Alopecurus aequalis	9.60	22)
Reinshof, Germany	Gleysol	Several yrs. unmanaged	–0.27	23)
Canstein, Germany	Gleyic Cambisol	10 yrs. old unmanaged fallow	–0.22	16)

to be continued on page 11

Appendix Part 3

Soil and land use unit	Soil type	Vegetation	CH_4-C flux	Reference
			kg ha^{-1} yr^{-1}	
ARABLE LAND				
Peat bog				
Napierville/ St. Clotilde, QC Canada	Drained peat bog	Horticultural crops	–0.24	24)
Non-illuvial soil				
Gullane, UK	Brown forest soil	Wheat	–2.24	8)
Scheyern, Germany	Dystric Eutrochrept	Potato	0.23	25)
Scheyern, Germany	Dystric Eutrochrept	Barley, leguminous crops, Sunflower	–0.35	26)
		Barley, Mustard, Wheat	–0.40	
	Typic Udifluvent	Barley, Mustard, Wheat	–0.57	
Illuvial soil				
Copenhagen, Denmark	Udalf	Rape, Wheat, Barley	–0.22	27)
Scheyern, Germany	Vertic Eutrochrept	Barley, leguminous crops, Sunflower	–35	26)
Hydromorphic soil				
Copenhagen, Denmark	Aquept	Wheat, Spinach	–0.11	5)
Reinshof, Germany	Gleysol	Wheat	–0.37	23)
		Rape	–0.42	
		Barley	–0.35	
WETLAND				
Peat bog				
St. Bruno, QC Canada	Domed bog	Sphagnum	0.75	28)
Upper Pine Marten Brook, NS Canada	Peat bog	Sphagnum	28	29)
Itasca County, MN USA	Peat	Forested bog, hummock	27.38	30)
		Forested bog, hollow	104	
		Open bog	323	
Woods Lake, NY USA	Terric Borosaprist (Bog)	Sphagnum, sedges, shrubs, red spruce	33.12	1)
Buck Hollow Bog, MI USA	Peat Bog	Sphagnum, Scheuchzeria palustris	537	31)
Big Cassandra Bog, MI USA	Peat Bog	Sphagnum, Carex calyculata	78	
	Peat Bog	Sphagnum, Carex oligosperma	194	
Big Run Bog, WV USA	Peat bog	Sphagnum, Eriophorum, Polytrichum	4.82	32)
Fen/swamp				
St. Bruno, QC Canada	Basin swamp	Populus deltoides	32	28)
		Betula, Tsuga	9	
Itasca County, MN USA	Peat	Fen lagg	95.81	30)
		Open poor fen	493	
New Hampshire, USA	Fen peat	Fen	0.37	
			0.80	31)
Vejlerne Reserve, Denmark	Fen	Phragmites australis	470	33)
Peaty mineral soil				
Klarer Pfuhl, Germany	Loamy silt	Typha latifolia	9.6	34)
Breites Fenn, Germany	Silty sand	Phalaris arundinacea	330	
Krummer Pfuhl, Germany	Silty sapropel	Sparganium erectum, Bidens.	200.3	
	Silty sand		72.8	

[1]) Yavitt et al. 1993a, 2) Castro et al. 1995, 3) Bowden et al. 2000, 4) Macdonald et al. 1997, 5) Ambus a. Christensen 1995, 6) Keller et al. 1983, 7) Crill et al. 1991, 8) Dobbie a. Smith 1996, 9) Priemé a. Christensen 1997, 10) Brumme a. Borken 1999, 11) Born et al. 1990, 12) Steinkamp et al. 2001, 13) Fiedler et al. 2005, 14) Hahn et al. 2000, 15) Ishizuka et al. 2000, 16) Teepe a. Brumme 1998, 17) van den Pol-van Dasselaer et al. 1997, 18) Flessa et al. 1998, 19) Mosier et al. 1993, 20) Sitaula et al. 2000, 21) Flessa et al. 1996, 22) Merbach et al. 1996, 23) Schmädeke et al. 1998, 24) Glenn et al. 1993, 25) Flessa et al. 2002, 26) Flessa et al. 1995, 27) Ambus a. Christensen 1995, 28) Moore a. Knowles 1990, 29) Dalva et al. 2001, 30) Dise 1993, 31) Shannon a. White 1994, 31) Bartlett a. Harriss 1993, 32) Yavitt et al. 1993b, 33) Brix et al. 2001, 34) Merbach et al. 2002.

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