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Modeling carbon sequestration under zero tillage at the regional scale. I. The effect of soil erosion

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ABSTRACT

Zero tillage is recognized as a potential measure to sequester carbon dioxide in soils and to reduce CO_2 emissions from arable lands. An up-scaling approach of the output of the Environmental Policy Integrated Climate (EPIC) model with the information system SLISYS-BW has been used to estimate the CO_2-mitigation potential in the state of Baden-Württemberg (SW-Germany). The state territory of 35,742 km^2 is subdivided into eight agro-ecological zones (AEZ), which have been further subdivided into a total of 3976 spatial response units. Annual CO_2-mitigation rates where estimated from the changes in soil organic carbon content comparing 30 years simulations under conventional and zero tillage. Special attention was given to the influence of tillage practices on the losses of organic carbon through soil erosion, and consequently on the calculation of CO_2-mitigation rates. Under conventional tillage, mean carbon losses through erosion in the AEZ were estimated to be up to 0.45 Mg C ha^{-1} a^{-1}. The apparent CO_2-mitigation rate for the conversion from conventional to zero tillage ranges from 0.08 to 1.82 Mg C ha^{-1} a^{-1} in the eight AEZ, if the carbon losses through soil erosion are included in the calculations. However, the higher carbon losses under conventional tillage compared to zero tillage are composed of both, losses through enhanced CO_2 emissions, and losses through intensified soil erosion. The adjusted net CO_2-mitigation rates of zero tillage, subtracting the reduced carbon losses through soil erosion, are between 0.07 and 1.27 Mg C ha^{-1} a^{-1} and the estimated net mitigation rate for the entire state amounts to 285 Gg C a^{-1}. This equals to 1045 Gg CO_2-equivalents per year with the cropping patterns in the reference year 2000. The results call attention to the necessity to revise those estimation methods for CO_2-mitigation which are exclusively or predominantly based on the measurements of differential changes in total soil organic carbon without taking into account the tillage effects on carbon losses through soil erosion.

1. Introduction

Soil carbon sequestration implies the removal of atmospheric CO_2 by plants and storage of the fixed C through incorporation into soil organic matter (Lal, 2004). The strategy is to increase SOC, improve depth distribution of SOC and stabilize SOC by encapsulating it within stable micro-aggregates so that C is protected from microbial processes or as recalcitrant C with long turnover time. Post and Kwon (2000) show that carbon sequestration can be promoted in agricultural

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land through appropriate agro-ecosystem management like the conversion of land under conventional tillage (ploughing) into reduced or zero tillage. Regional estimates of soil carbon sequestration potential of agricultural practices are crucial if policymakers are to decide on agro-policy measures with the aim of reducing national CO_2 emissions (Falland et al., 2002). Soil carbon sequestration estimation is normally used for large heterogeneous areas, mainly regional scale, while direct soil carbon sequestration measurements are applied for small homogenous areas (Janzen, 2004). Three main methods have been used to estimate changes in regional SOC: (1) up-scaling of the results of simple regression models between time and differences in organic carbon stocks between different treatments (Gupta and Rao, 1994; Kern and Johnson, 1993), (2) up-scaling of mitigation factors provided by the IPCC inventory method, which consists in a database of changes in C stocks resulting from land use change over the inventory period of 20 years (IPCC, 1997), (3) up-scaling of the output of dynamic models linked to spatial databases or geographic information systems (GIS) (Falland et al., 2002; Wang et al., 2002; Ardö and Olsson, 2003; Yadav and Malanson, 2008). The last approach allows dynamic estimates taking into account the distribution of soil characteristics, meteorological conditions and land use and permits geographic areas of particular soil carbon sequestration potential to be identified. Some of the most prominent numeric models applied in the estimation of carbon sequestration from the plot to the regional scale are CENTRURY (Yadav and Malanson, 2008), RothC (Van Wesemael et al., 2005) and EPIC (Causarano et al., 2007; Doraiswamy et al., 2007; Izaurralde et al., 2007; Thomson et al., 2006). Soil erosion is an important process influencing carbon turnover and carbon sequestration, but is often neglected when comparing the carbon stocks of soils under different tillage practices at the field scale (Polyakov and Lal, 2008; Doraiswamy et al., 2007). The same holds for the estimation of the effects of changes in tillage on soil carbon stocks at the regional scale, where only few studies at watershed or county level try to separate the carbon sequestration effect of reduced or zero-tillage from the carbon protection effect against soil erosion (Izaurralde et al., 2007).

In this paper, the up-scaling of the output of the simulation model EPIC (Williams, 1995) has been used to estimate the CO_2-mitigation potential of the adoption of zero tillage practices compared to traditional ploughing systems and to evaluate the effect of soil erosion on the estimation procedure in the state of Baden-Württemberg (Southern Germany) and its eight agro-ecological zones.

2. Methods

All steps necessary for the creation of model input files, running the simulations and up-scaling of the results are components of the information system SLISYS-BW (Soil and Land Resources Information System for the state of Baden-Württemberg). The information system is an upgrade of SLISYS-Neckar (Gaiser et al., 2006a,b) and contains besides primary data related to land characteristics and land use the agro-ecosystem model EPIC.

2.1. *The EPIC model*

EPIC is a field-scale model that is designed to simulate drainage areas that are characterized by homogenous weather, soil, landscape, crop rotation, and management system parameters (Williams, 1995). EPIC operates on a continuous basis using a daily time step and can perform long-term simulations for hundreds of years. A wide range of crops and management practices can be simulated with the generic crop growth routine. An extensive array of tillage systems and other management practices can also be simulated with the model. Weather information is input as long-term monthly means including standard deviations and daily data if available. If daily weather data is not available, a statistical weather generator produces daily estimates for precipitation, minimum and maximum temperature, radiation, relative humidity and wind speed from the monthly means. Soil data are required per soil profile with a maximum of ten horizons with texture, soil pH, and organic carbon content as minimum information.

One main reason for choosing EPIC (Version 3060) for the estimation of carbon sequestration is the improved C and N turnover routine. Recently, Izaurralde et al. (2006) replaced the former EPIC carbon turnover routine by adding a new carbon and nitrogen turnover module based on the CENTURY model (Parton et al., 1994). Initial tests of the improved carbon cycling routine have been performed by Izaurralde et al. (2006) for five Great Plains sites located in Nebraska, Kansas, and Texas, and for a 60-year rotation experiment located near Breton, Alberta. It was concluded from these studies that the model satisfactorily replicates the soil carbon dynamics over a range of environmental conditions, cropping/vegetation and management systems. For the state of Baden-Württemberg, testing has been carried out by Billen et al. (2008) on different sites under conventional and reduced tillage as well as sites where cropland was converted into grassland. The same model version was recently used for the assessment of CO_2 emission scenarios in the EU25 (Schmid et al., 2007).

In addition EPIC has the ability to simulate at the same time carbon balance and erosion by water and wind. This is different from other carbon turnover models like CENTURY or RothC (Parton et al., 1994; Jenkinson, 1990). CENTURY can consider carbon loss through soil erosion when being defined as boundary condition through input from other sources. However, this may not be sufficient, because in this case the feed back between soil erosion, carbon assimilation by crops and carbon sequestration in the soil is not taken into account. EPIC provides the possibility to estimate soil erosion by water from five different equations: (i) the Universal Soil Loss Equations (USLE) (Wischmeier and Smith, 1978), (ii) four approaches of the modified Universal Soil Loss Equations (MUSLE, Theoretical MUSLE, MUSLE for small watersheds and MUSI) (Williams, 1975), (iii) the Onstad–Foster modification of Onstad–Foster (Onstad and Foster, 1975) and (iv) RUSLE (Renard et al., 1997). In this paper the MUSLE approach is used where the erosivity factor R of the Universal Soil Loss Equation is replaced by the simulated daily surface run-off, which allows for a better temporal resolution of soil erosion events and assessment of soil erosion due to snowmelt processes (Puurveen et al., 1997). The factors in the MUSLE equation for each simulation unit where estimated by the model, depending on soil type, topographical information and crop development.

2.2. Study area and simulation units

With an area of 35,742 km^2 the state of Baden-Württemberg is the third largest state in Germany. The climate is temperate humid. Depending on the location, the mean annual temperature is between 4 and 11 °C and the annual precipitation ranges between 600 and 2200 mm (DWD, 2006). The state area has been subdivided by the state ministry for rural development into eight zones with similar agro-ecological and economic conditions (MLR, 2003). The eight agro-ecological zones (AEZs) are namely: Rhein/Bodensee, Schwarzwald, Alb/Baar, Oberland/Donau, Allgäu, Unterland/Gäue, Bauland/Hohenlohe, and Albvorland/Schwäbischer Wald (Fig. 1). Mean annual temperature varies between 5.1 and 9.0 °C whereas mean annual rainfall is between 711 and 1552 mm (Table 1). Soil units are highly variable due to the undulating landscape and heterogeneous parent materials with Cambisols and Luvisols as the main soil groups. Crop rotations are predominantly 3-year rotations. In addition 2- and 4-year rotations can occur. The major crops in the rotations are winter cereals, summer cereals and corn, which is used mainly for silage, except in AEZ Rhein/Bodensee and Unterland/Gäue. For this study, the AEZs were further subdivided into a total of 3976 smaller units called LUSACs (Land Use-Soil Association-Climate). Each LUSAC unit has a minimum surface of 1 ha and represents an area with similar climate conditions, soil characteristics and the same crop and soil management. The subdivision was carried out in three steps:

1. Definition of regions with similar climatic conditions
2. Definition of spatial distribution of land use/land cover types (LfU, 2002)
3. Overlay of the previous geometries with the soil association map of Baden-Württemberg (BÜK200, LGRB, 1995)

Before overlaying the maps, further refinement was needed for the land use/land cover map, since under the land cover class “agricultural land” the map distinguishes only grassland, arable land, fallow, and plantations (vineyards and orchards). Representative crop rotations for each AEZ (Table 1) where defined with their respective share in order to match the

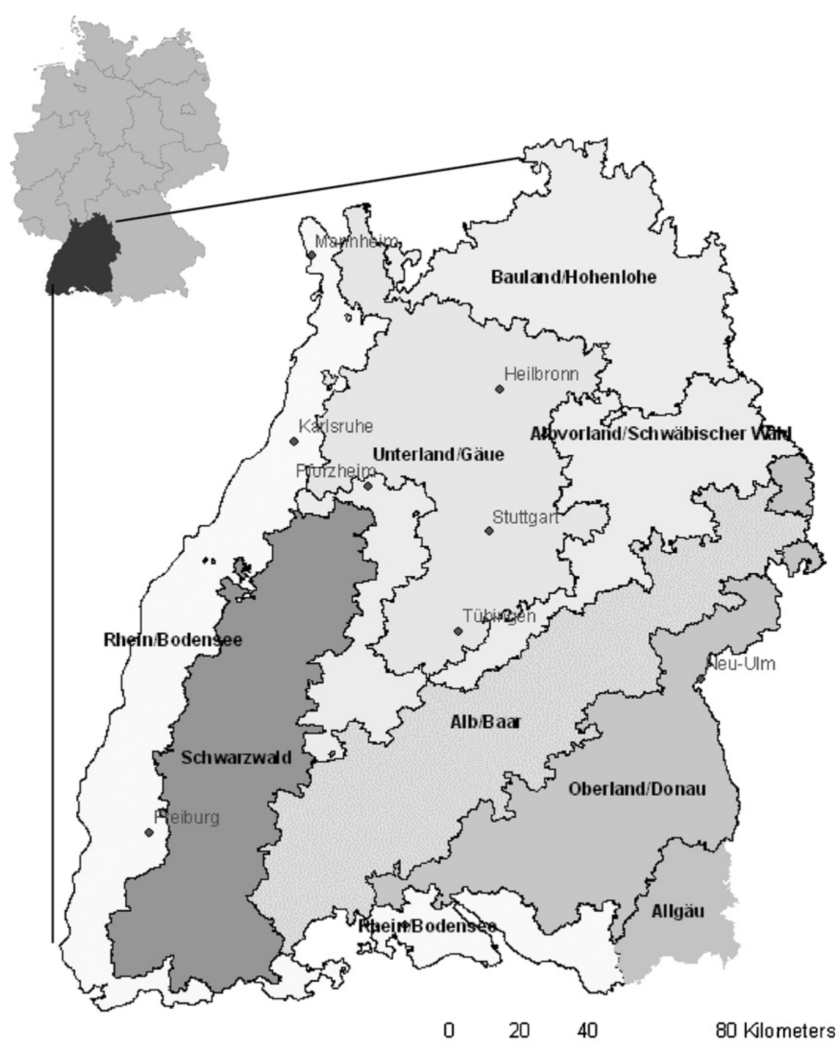

Fig. 1 – The state of Baden-Württemberg and its subdivision into eight agro-ecological zones.

Table 1 – Some characteristics of the eight agro-ecological zones (AEZ) in Baden-Württemberg

Agro-ecological zone	Station name	Mean annual temperature (°C)	Mean annual rainfall (mm)	Dominant crop rotations	Cropland (ha)	Proportion of winter cereals in the year 2000	Number of LUSAC units
Unterland/Gäue	Heilbronn	9.0	711	WWHT-WWHT-SWHT WWHT-SWHT-RAPE WWHT-SBET-SWHT-CORN	146,171	42	552
Rhein/Bodensee	Offenburg	8.8	893	CORN-WWHT-WWHT WWHT-WWHT-SWHT	113,028	75	672
Schwarzwald	Schwarzwald Süd	5.7	1552	WWHT-SWHT-RAPE CLOV-CLOV-WWHT WWHT-SWHT-WWHT-SILC	11,362	42	432
Alb/Baar	Münsingen-Apfelstetten	5.1	961	WWHT-SWHT-SILC WWHT-WWHT-SWHT WWHT-SWHT-WWHT-RAPE	91,636	43	789
Allgäu	Kempten	6.1	1268	WWHT-SWHT-SILC CLOV-CLOV-WWHT SILC-WWHT-WWHT SILC	1,470	22	200
Oberland/Donau	Biberach	6.8	845	WWHT-SWHT-SILC SILC-WWHT-WWHT WWHT-SWHT-WHT-RAPE	143,477	43	702
Albvorland/Schwäbischer Wald	Friedrichshafen	8.3	989	WWHT-RAPE-SILC-SWHT CLOV-CLOV-WWHT	15,382	24	371
Bauland/Hohenlohe	Künzelsau	6.4	850	WWHT-SWHT-RAPE SILC-WWHT-WWHT WWHT-SWHT	133,746	39	258
Total					656,273		3976

WWHT: winter cereals; SWHT: summer cereals; CORN: corn; SIL: corn silage; CLOV: clover/grass; RAPE: canola; POTA: potato; SBET: sugar beet.

Table 2 – Coverage and mean total organic carbon content (TOC) of soil groups/soil units according to the soil world reference base (WRB, 2006) and the German classification system in the arable land of Baden-Württemberg

WRB 2006	German classification	TOC (kgC/m^2)	km^2	%
Cambisols	Braunerde	9.9	649	9.9
Podzols	Podsol	7.5	5	0.1
Luvisols	Parabraunerde	9.8	2750	42.1
Other Anthrosols	Kultisole	8.0	23	0.4
Fluvic Cambisols	Auenbraunerde	18.3	442	6.8
Fluvisols	Auenpararendzina	14.5	65	1.0
Clayey Cambisols	Terra fusca	10.2	139	2.1
Vertic Cambisols	Pelosol	10.8	622	9.5
Gleysols	Gleye	14.4	299	4.6
Rendzic Leptosols	Rendzina	11.6	631	9.7
Stagnic Luvisols	Stagno-/Pseudogley	10.9	181	2.8
Calcaric Regosols	Pararendzina	6.8	590	9.0
Chernozems	Tschernosem	18.5	19	0.3
Cumulic Anthrosols	Kolluvisol	14.2	115	1.8
			6530	100

share of the individual crops on the arable land within each AEZ provided by the statistical office of Baden-Württemberg (StaLa, 2003). Then, the different crop rotations where distributed randomly on the arable land of each AEZ. Soil and topographical information including slope inclination and length was extracted from the water and soil atlas of Baden-Württemberg (LfU, 2004). More than 40% of the arable land in Baden-Württemberg is dominated by Luvisols, which are in most cases slightly acid to acid in the topsoil and neutral or slightly calcareous in the subsoil (Table 2). Then Cambisols either loamy (typical Cambisols) or clayey (Clayey and Vertic Cambicols) follow with about 20%. According to the humid to per-humid climate soils tend to be slightly acid to acid, whereas the texture is usually more loamy-clayey than sandy-loamy or sandy.

The overlay of the land use map with the soil and terrain information of the BÜK200 (with 394 soil associations) yielded a total of 3976 response units (Table 1).

2.3. *Simulation of carbon sequestration and erosion*

The estimation of soil organic carbon changes was done according to the slightly modified procedure described by Gassman et al. (2003). The procedure consists in the following steps (Fig. 2).

- Preparing EPIC input database files for all LUSAC units.
- Running the simulations for each LUSAC unit.
- Extracting the output files and transferring to the database.
- Analyzing the results.

In each AEZ a representative climate station was selected. Since the simulation period was 30 years, long-term monthly means (years 1987–2003) of minimum temperature and maximum temperature and the monthly sum of precipitation were used to characterize the climatic conditions in each AEZ. Daily values for the simulations were then produced by the weather generator based on the monthly means and standard deviations. For the calculation of the potential ET the approach given by Hargreaves and Samani (1985) was used.

For the simulation runs only the dominant soil type in each soil association was used. However, each soil type was represented by one or several soil profiles, because the variability of soil properties within certain soil groups can be relatively high. This implies that within each soil group individual simulations were carried out for each soil profile and then the results where aggregated to the soil group level. Required terrain information (inclination) and soil information (depth of each soil horizon, bulk density, texture, organic carbon, organic nitrogen, pH, coarse fragment content, CEC) was extracted from a soil database containing 333 soil profiles. In order to simulate the crop management, recommended crop and soil operations were gathered in chronological order in management sets of twelve crop rotations (Table 1). Two tillage options were distinguished:

a. Conventional tillage (mouldboard plough)
b. Zero tillage (direct seeding into crop residues of the previous crop without any soil tillage)

and combined with the management sets of the crop rotations. In the simulations it was assumed that all crop residues remain in the field. In order to estimate the carbon losses through water erosion the Modified Universal Soil Loss Equation (MUSLE) was used. Representative crop rotations have been defined for each AEZ (Table 1). Each crop rotation has a specific coverage in order to match the coverage of the individual crops as given by the statistical bureau of Baden-Württemberg (StaLa, 2003).

2.4. *Data analysis and aggregation*

In a first step, the total organic carbon change (TOCC) in each LUSAC after a simulation period of 30 years taking into account soil erosion processes (PEC = 1) was calculated as

$$\mathrm{TOCC_{LUSAC}} = \frac{(\mathrm{Av\_WOC_{26-30}} - \mathrm{Av\_WOC_{1-5}})}{25} \qquad (1)$$

where $\mathrm{TOCC_{LUSAC}}$ is the total organic carbon change in $\mathrm{Mg\,C\,ha^{-1}\,a^{-1}}$ over the entire soil profile; $\mathrm{Av\_WOC_{26-30}}$ is the

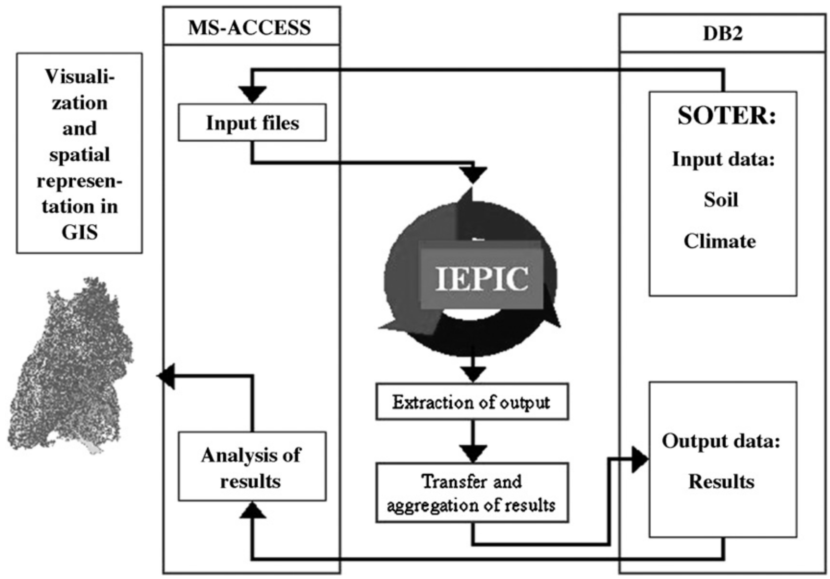

Fig. 2 – Workflow for the up-scaling of EPIC simulation results to the state level.

average of total organic carbon $Mg\,C\,ha^{-1}\,a^{-1}$ in the soil over the last 5 years of simulation; Av_WOC_{1-5} is the average of total organic carbon t/ha in the soil over the first 5 years of simulation.

The simulation results for individual LUSACs showed in some cases annual fluctuations of total organic carbon stocks, which called for a smoothening of the start and end values (Fig. 2). Therefore, the averages of the first and the last 5 years were used instead of simply taking the difference between the last and the first years. The value of 25 in the Eq. (1) represents the 25 years period between the mean of the last 5 years (27.5) and the mean of the first 5 years (2.5). The calculation of an annual average assumes that the soil organic carbon changes can be approximated to a linear trend, which is the case in most LUSACs within the simulation period of 30 years (compare Section 3).

$TOCC_{LUSAC}$ was calculated for both conventional and zero tillage treatments. The so-called apparent CO_2–C mitigation rate $\Delta CO_2–C_a$ (Mg C/ha/year) for the shift from conventional to zero tillage in each LUSAC is then the difference between the $TOCC_{LUSAC}$ in the conventional and the zero-tillage treatment. It is called the apparent CO_2-mitigation rate because differences between the two tillage practices with respect to carbon losses through erosion are not taken into account. However, Fig. 3 shows that, in particular in conventional systems, an appreciable amount of carbon is lost through erosion (reflected as the difference between TOC and net TOC in Fig. 3). Therefore, in the next step, the net change in total organic carbon (net TOCC) which is the sequestered organic carbon in each LUSAC (SOC_{LUSAC}) was calculated by adding the mean annual organic carbon loss in eroded sediments to the total organic carbon change as

$$SOC_{LUSAC} = netTOCC_{LUSAC} = TOCC_{LUSAC} + OCES_{LUSAC} \quad (2)$$

where SOC_{LUSAC} is the annual sequestered organic carbon in $Mg\,C\,ha^{-1}\,a^{-1}$; $netTOCC_{LUSAC}$ is the net annual total organic carbon change in $Mg\,C\,ha^{-1}\,a^{-1}$ excluding carbon losses through soil erosion; $TOCC_{LUSAC}$ is the gross annual total organic carbon change in $Mg\,C\,ha^{-1}\,a^{-1}$; $OCES_{LUSAC}$ is the mean annual organic carbon loss in eroded sediments in $Mg\,C\,ha^{-1}\,a^{-1}$.

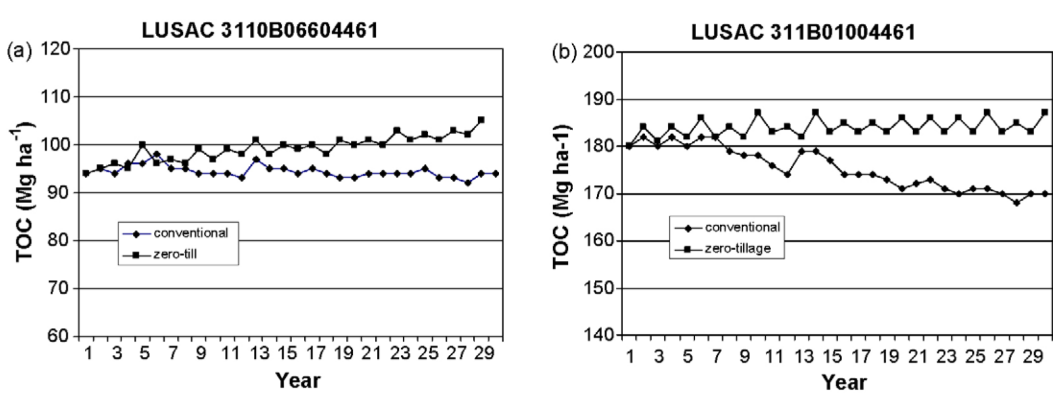

Fig. 3 – Temporal behavior of total organic carbon stocks (TOC) including soil carbon losses through soil erosion in two individual LUSACs (Land Use-Soil Association-Climate units) under conventional and zero-tillage.

The addition of carbon lost through erosion to the change in total organic carbon is a mathematical procedure to calculate the fraction of change in the total organic carbon stock that is due to CO_2-fixation and to separate it from the changes caused by carbon losses through erosion. The addition of the eroded carbon does not mean that the eroded sediments are re-deposited in the LUSACs during the simulation runs. Rather it is assumed in this paper that the carbon in eroded sediments is no longer influencing the CO_2-emissions in the simulations, i.e. it is either deposited in the flow channels or evacuated to the sea. To which extend the eroded and re-deposited sediments are neutralized by being buried or a sink or source of CO_2 is controversially discussed (Izaurralde et al., 2007; Polyakov and Lal, 2008; Quine and Van Oost, 2007; Van Oost et al., 2007; Berhe et al., 2007).

The net CO_2-mitigation rate $\Delta CO_2–C_r$ ($Mg\,C\,ha^{-1}\,a^{-1}$) of zero tillage in each LUSAC is then the difference between the SOC_{LUSAC} in the conventional and the zero-tillage treatment. Data aggregation from the LUSAC level to both AEZ and state level was carried out by calculating the area weighted averages of the apparent and the net CO_2-mitigation rates taking into account the area share of each LUSAC unit. Total CO_2-mitigation rate is calculated as

$$\Delta CO_2 - C_{rt} = \sum_{i}^{N} \Delta CO_2 - C_{ri}\,Area_{LUSACi}$$

where $\Delta CO_2–C_{rt}$ is the net total mitigation rate per AEZ in $Gg\,a^{-1}$; $\Delta CO_2–C_r$ is the net mitigation rate in LUSAC unit i in $Mg\,C\,ha^{-1}\,a^{-1}$; $Area_{LUSACi}$ is the area of LUSAC unit i in the respective AEZ in ha.

Statistical analysis was performed with the t-test for pair wise comparison of treatment means.

3. Results and discussion

3.1. *Temporal behavior of total soil organic carbon stocks*

The example of two individual LUSACs in Fig. 3 shows, that the temporal evolution of the soil carbon stocks can be very variable. Two different sites out of more than 3000 LUSACs are presented. On the first site (under a 4-years rotation with winter wheat-sugar beet, winter barley and corn), it seems that carbon content is at a steady state for conventional tillage from the beginning of the 30 years simulation. However, this is not the case for the zero-tillage practice (Fig. 3a). The second site under the same rotation constantly losses carbon under conventional tillage due to mineralization of organic carbon and soil erosion, whereas soil organic carbon content slightly increases under zero-tillage. Usually, zero-tillage leads to an increase in the amount of soil organic carbon, whereas conventional tillage rather causes a decrease or maintains carbon content at the same level. In many cases, the simulation period was not sufficient to reach the steady state conditions, i.e. the equilibrium between C inputs and C outputs (Fig. 3). Steady state equilibrium requires constant climatic, soil and management conditions (i.e. constant C inputs, constant tillage practice etc.) for a sufficiently long period. These prerequisites are fulfilled in forest soils or native grassland soils, or in long-term agricultural experiments, where the treatments did not change with time. However, within the state of Baden-Württemberg, there are few sites which are in a "steady state", because the management conditions are continuously changing due to changes in agricultural policies, markets and technologies. At the same time soil conditions are also changing due to the process of soil erosion. The simulations show that the system is very dynamic and soil erosion is an important factor to disturb the steady state equilibrium. On many sites, it prevents the system to reach a steady state, at least within the applied simulation time of 30 years.

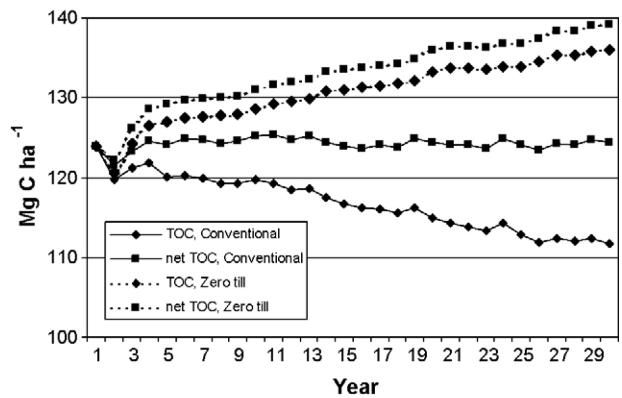

Fig. 4 – Simulated temporal evolution of total organic carbon stocks including (TOC) and excluding (net TOC) carbon losses through soil erosion under conventional and zero-tillage in the agro-ecological zone Rhein/ Bodensee.

When the temporal dynamics of total organic carbon stocks are analyzed in an aggregated form at the regional scale, the same trend persists. As an example the evolution of the soil organic carbon stock under conventional and zero-tillage in the AEZ Rhein/Bodensee is presented in Fig. 4. When losses through soil erosion are included, then the decrease of the soil organic carbon stock is considerable under conventional tillage (TOC, conventional in Fig. 4). If the carbon losses through soil erosion are excluded, then the carbon stock over the whole AEZ is almost maintained under conventional tillage, signifying that without erosion the carbon status at the applied management level and over the whole AEZ is in a near steady state (net TOC, conventional in Fig. 4). Changing the tillage practice to zero-tillage disturbs the steady state and leads to a nearly linear increase of the average soil organic carbon stock within the 30 years simulation period. Carbon losses due to soil erosion are much lower under zero-tillage compared to the conventional tillage. The difference between the initial (TOC_0) and the final total organic carbon content (TOC_{30}) is the apparent CO_2-sequestration or -emission, because it includes losses of carbon through soil erosion. It is always higher than the net CO_2-sequestration or -emission, which is the difference between TOC_0 and the net TOC_{30} at the end of the simulation period for both conventional and zero-tillage systems.

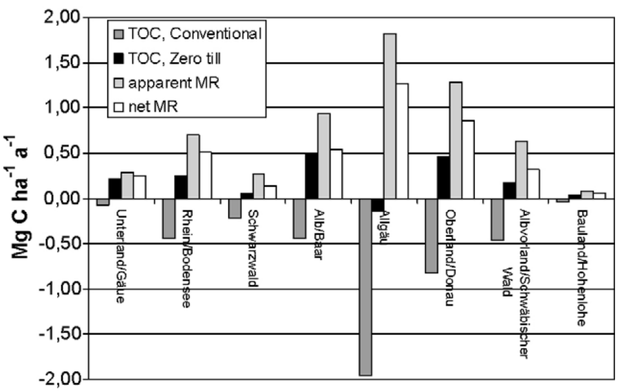

Fig. 5 – Simulated annual soil organic carbon changes (TOC) including erosion effects in arable land under conventional and zero tillage over 30 years in eight agro-ecological zones in Baden-Württemberg and the effects on apparent (apparent MR) and net CO_2-mitigation rates (net MR).

3.2. CO_2-mitigation potential and carbon losses through soil erosion

Fig. 5 shows the mean annual soil organic carbon changes (TOCC) in the eight agro-ecological zones (AEZ) under conventional and zero tillage including the carbon losses through soil erosion. Under conventional tillage, there are losses of organic carbon in all AEZ in the range of 0.04–1.95 Mg C ha^{-1} a^{-1}. In contrast, zero tillage decreases soil organic carbon pools only in one AEZ (Allgäu), but increases soil organic carbon in all other AEZ. Highest increases in soil organic carbon occur in the AEZ Alb/Baar, Oberland/Donau and Rheintal/Bodensee under zero-tillage. These AEZ are regions with a high proportion of cereals and rape which have high potentials of carbon sequestration due to the large amounts of crop residues left in the field. Lal (1997) identified crop residues of having an important potential in sequestering carbon in soils. If 15% of C contained in crop residues can be converted to passive soil organic carbon fraction, it may offset more than 40% of the annual increase of carbon dioxide in the atmosphere. Duiker and Lal (1999) found a linear relationship between the amount of crop residues and carbon sequestration in Stagnic Luvisols of Central Ohio. On the other hand, the highest losses of soil organic carbon per hectare occur in the region with lowest mean temperature and highest annual rainfall for both conventional and zero tillage (AEZ Allgäu). This can be attributed to the fact that soils with high organic matter content (Humic Gleysoils, Histosols) have the highest coverage in this AEZ. When these soils are cultivated with the conventional plough, large amounts of CO_2 are released (Lohila et al., 2003; Chimner and Cooper, 2003).

The effect of conventional and zero tillage on carbon losses through soil erosion determine considerably the CO_2-mitigation rates. If carbon losses through soil erosion are included in the calculations of the soil organic carbon changes, then the highest (apparent) CO_2-mitigation rates are above 1.5 Mg C ha^{-1} a^{-1}. However, when the carbon losses through erosion are excluded and the net CO_2-mitigation rates are calculated, then the rates are reduced by up to 50% (Albvorland/Schwäbischer Wald). The reduction is highest in AEZs with high amounts of rainfall, lower temperatures and undulated to steep topography (Schwarzwald, Albvorland/Schwäbischer Wald, Alb/Baar, Oberland/Donau). These regions have also highest erosion rates except for the AEZ Schwarzwald (Table 3). In the AEZ Schwarzwald erosion is relatively lower because the soils are predominantly sandy with high infiltration rates and the rotations include perennial clover grass where the soil is covered for at least two consecutive years. The shift from conventional ploughing to zero-tillage almost eliminates erosion and hence reduces the apparent CO_2-mitigation rates (Table 3 and Fig. 5) (Fu et al., 2006; Carroll et al., 1997).

The mean net CO_2 mitigation rates in the AEZs differ significantly in almost all pair wise comparisons (Table 4). The highest net mitigation rate when shifting from conventional to zero tillage is found in the AEZ Allgäu. Fig. 5 indicates that this is rather the consequence of a strong reduction of soil organic matter mineralization under zero tillage than carbon sequestration by building up soil organic matter. The AEZ Allgäu has the highest percentage of soils with pronounced organic matter accumulation (Histisols, Humic Gleysols) due to the temperate, humid climate, topography, soil genesis and predominant use of these soils as grassland. Hence, when turned into cropland by conventional tillage intensive mineralization of soil carbon occurs, which is lower under zero tillage. Elevated net CO_2-mitigation rates occur also in the AEZ Oberland/Donau and Alb/Baar. There, net mitigation rates are associated with soil organic carbon increases under zero tillage (Fig. 5), which can be explained by the larger proportion of winter cereals on the cropland in connection with relatively low temperature (Table 1). In fact, AEZ Rhein/Bodensee

Table 3 – Estimated mean annual losses of organic carbon through soil erosion (OCES) in Mg C ha^{-1} a^{-1} in eight agro-ecological zones of Baden-Württemberg

Agro-ecological zones	Conventional	Zero till	Difference
Oberland/Donau	−0.45	−0.03	−0.42
Alb/Baar	−0.40	−0.02	−0.38
Albvorland/Schwäbischer Wald	−0.36	−0.04	−0.32
Allgäu	−0.29	−0.02	−0.27
Rhein/Bodensee	−0.21	−0.03	−0.18
Schwarzwald	−0.13	−0.01	−0.12
Unterland/Gäue	−0.03	0.00	−0.03
Bauland/Hohenlohe	−0.01	0.00	−0.01

Table 4 – Significance levels of pair wise comparisons between agro-ecological zones with respect to their net CO_2 mitigation rates when the tillage system is converted from conventional to zero-tillage

AEZ		Unterland/Gäue	Rhein/Bodensee	Schwarzwald	Alb/Baar	Allgäu	Oberland/Donau	Albvorland/Schwäb. Wald	Bauland/Hohenlohe
		1	2	3	4	5	6	7	8
Unterland/Gäue	1	–	***	**	**	***	***	n.s.	***
Rhein/Bodensee	2	***	–	***	n.s.	**	***	***	***
Schwarzwald	3	**	***	–	***	***	***	***	***
Alb/Baar	4	***	n.s.	***	–	**	***	*	***
Allgäu	5	***	**	***	**	–	*	***	***
Oberland/Donau	6	***	***	***	***	*	–	***	***
Albvorland/Schwäb. Wald	7	n.s.	***	***	*	***	***	–	***
Bauland/Hohenlohe	8	***	***	***	***	***	***	***	–

*$P < 0.05$, **$P < 0.01$, ***$P < 0.001$ for H_0; $\mu_1 = \mu_2$ for pair wise comparisons.

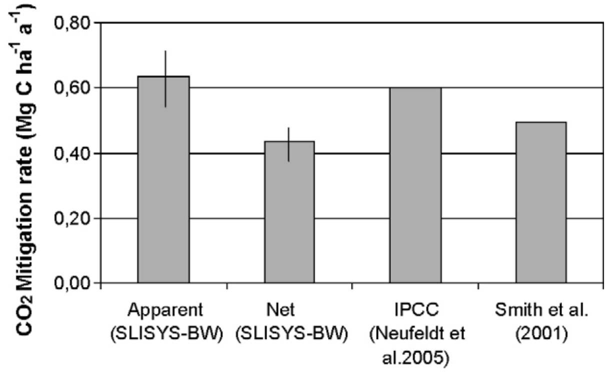

Fig. 6 – Simulated annual CO_2-mitigation rates in cropland due to the change from conventional to zero tillage over 30 years (averaged over the state of Baden-Württemberg) compared to mitigation rates in the literature (standard deviation as error bars).

has the highest proportion of winter cereals, but net increase of soil organic carbon under zero tillage is lower due to higher mean temperatures compared to AEZ Alb/Baar and Oberland/Gäue. Thus, the complex interactions of the driving forces climate, crop distribution and soil type determine the net CO_2-mitigation rates in the AEZs.

Since the influence of erosion intensity is not explicitly considered in the conventional assessment methods for CO_2-mitigation caused by tillage changes, it is difficult to compare the values derived from SLISYS-BW with, e.g. the values provided by the IPCC method (IPCC, 1997). Neufeldt (2005) gives for the state of Baden-Württemberg an average CO_2-mitigation rate of zero tillage of 0.6 Mg C ha^{-1} a^{-1} according to the IPCC method. This value corresponds to the area-weighted average apparent CO_2-mitigation rate calculated with SLISYS-BW, which amounts to 0.63 Mg C ha^{-1} a^{-1} (Fig. 6). Since the database of the IPCC method relies mostly on literature studies based on total carbon changes in soils and without explicit consideration of soil erosion effects, it relates more to the apparent CO_2-mitigation rate. The net annual CO_2-mitigation rate derived from SLISYS-BW (0.43 Mg C ha^{-1} a^{-1}) is closer to the mitigation rate of 0.49 Mg C ha^{-1} a^{-1} published by Smith et al. (2001), which is an average value over several field experiments. In any case, the net CO_2-mitigation rates which eliminate the effect of soil erosion are smaller than the rates calculated b the IPCC method or found in the literature and this in spite of the fact that the entire profiles where taken into account and not only the topsoil (0–30 cm) as in the estimation procedure proposed by the IPCC.

The results call attention to the necessity to revise the current methods for the estimation of CO_2-mitigation rates for different tillage practices if they are exclusively or predominantly based on measurements of total soil organic carbon changes without taking into account the tillage effects on carbon losses through soil erosion. Only those assessment methods which are based on carbon changes on sites without any erosion risk or based on direct measurements of CO_2 balances are producing reliable estimates of net CO_2-mitigation rates.

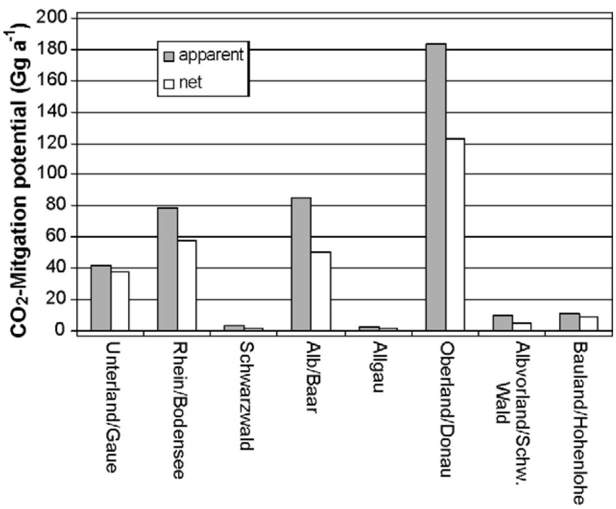

Fig. 7 – Simulated apparent and net CO_2-mitigation rates on arable land due to the change from conventional to zero tillage over 30 years in eight agro-ecological zones in the state of Baden-Württemberg.

With 123 Gg C ha^{-1} a^{-1} the total mitigation rate is highest in the AEZ Oberland/Donau due to the high mitigation rate per hectare and the relatively large area of cropland (Fig. 7 and Table 1). The AEZ Rhein/Bodensee, Alb/Baar and Unterland/Gäue are following with 58, 50, and 37 Gg C ha^{-1} a^{-1}, respectively. Under the actual land use and crop distribution patterns these four AEZs account for more than 90% of the CO_2-mitigation potential which amounts to a total of 285 Gg C ha^{-1} a^{-1} on cropland in the state of Baden-Württemberg under the current cropping practices.

4. Conclusions

The complex interactions between climate, crop distribution and soil type determine the carbon sequestration rates in the AEZs of Baden-Württemberg. Compared to the conventional assessment methods, the advantage of the calculation of CO_2-mitgation rates with the information system SLISYS-BW is the higher spatial and temporal resolution and the potential to consider dynamic changes of system processes and boundary conditions like loss of carbon through erosion, climate change or increasing shares of energy crops. The necessity to revise mitigation assessment methods that are based on the measurement of changes in soil organic carbon pools due to different tillage practices without consideration of soil erosion effects are demonstrated. More efforts should be put in the direct measurement of CO_2 fluxes from soils under conventional and zero tillage in a wide range of agro-ecological zones. Zero-tillage shows considerable potentials to sequester organic carbon in agricultural soils within a time period of 30 years. The relevance to mitigate the atmospheric warming necessitates the establishment of a complete greenhouse gas balance because there are indications that zero-tillage practices at the same time sequester CO_2 but increase N_2O-emissions. Other environmental side-effects through the more intensive application of herbicides under zero tillage should be considered as well when promoting new tillage systems.

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