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Soil erosion from sugar beet in Central Europe in response to climate change induced seasonal precipitation variations

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Abstract

This study estimates the implications of projected seasonal variations in rainfall quantities caused by climate change for water erosion rates by means of a modeling case study on sugar beet cultivation in the Central European region of Upper-Austria. A modified version of the revised Morgan–Morgan–Finney erosion model was used to assess soil losses in one conventional and three conservation tillage systems. The model was employed to a climatic reference scenario (1960–89) and a climate change scenario (2070–99). Data on precipitation changes for the 2070–99 scenario were based on the IPCC SRES A2 emission scenario as simulated by the regional climate model HadRM3H. Weather data in daily time-steps, for both scenarios, were generated by the stochastic weather generator LARS WG 3.0. The HadRM3H climate change simulation did not show any significant differences in annual precipitation totals, but strong seasonal shifts of rainfall amounts between 10 and 14% were apparent. This intra-annual precipitation change resulted in a net-decrease of rainfall amounts in erosion sensitive months and an overall increase of rainfall in a period, in which the considered agricultural area proved to be less prone to erosion. The predicted annual average soil losses under climate change declined in all tillage systems by 11 to 24%, which is inside the margins of uncertainty typically attached to climate change impact studies. Annual soil erosion rates in the conventional tillage system exceeded 10 t ha^{-1} a^{-1} in both climate scenarios. Compared to these unsustainably high soil losses the conservation tillage systems show reduced soil erosion rates by between 49 and 87%. The study highlights the importance of seasonal changes in climatic parameters for the discussion about the impacts of global climate change on future soil erosion rates in Central Europe. The results also indicate the high potential of adaptive land-use management for climate change response strategies in the agricultural sector.

Keywords: Climate change; Soil erosion; Precipitation; Sugar beet; Conservation agriculture; Erosion modelling

1. Introduction

Climate change of anthropogenic origin is widely accepted as being reality by most scientists (IPCC, 2001b). Weather records from meteorological stations around the world document a long-term trend of rising average global temperature of 0.6±0.2 °K over the 20th century (IPCC, 2001b). Besides temperature, climate change affects other weather parameters. Precipitation patterns are predicted to change and extreme weather events (floods, hurricanes, droughts, etc.) are likely to occur more frequently. Karl et al. (1996) quantified the chance to less than 1 in 1000 that the recent increase in extreme weather events and in the number of wet days in the USA could have taken place under a quasi stationary climate. But considerable uncertainty exists with regard to the specific character of climate change impacts, because most impacts will vary widely in scale, intensity and time of occurrence among different regions (IPCC, 2001a). Also the individual vulnerability and adaptive capacity of the affected biophysical and socioeconomic systems will strongly influence the severity of climate change impacts (IPCC, 2001a). It is likely that continued climatic change will aggravate the problem of accelerated soil erosion in most areas around the world, which are affected by human activities. This is especially true for agricultural land, where many parameters influencing the soil's vulnerability to erosion are likely to be

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altered with global warming, such as precipitation amounts and intensities. Plant growth conditions and agricultural practice may also change as land-use management strategies become adapted to a changing climate (e.g. Parry, 1990; Rosenzweig and Hillel, 1998; Williams et al., 2002). The specific degree of change in soil loss rates will depend on the climate sensitivity of each system and the intensity of local climate change effects.

Yang et al. (2003) estimated a global average increase in soil loss of 14% under climate change using a GIS-based RUSLE model (Revised Universal Soil Loss Equations (Renard et al., 1997)). They used a numerical climate change simulation and considered future changes in land cover based on actual and historical land-use data, present trends in land-use development and assumptions about future economic development. Lal (1994) pointed out, that such global estimations often depend on numerous extrapolations and assumptions, which are likely to produce huge errors. But there is also a small number of more specific modelling studies trying to appraise the potential impact of climate change on soil erosion rates for selected areas around the world (Table 1).

Table 1
Selected studies on regional impacts of climate change on soil erosion

Publication	Reseach design and results			
	Study area	Models and tools	Studied parameters	Soil erosion rate
Farvis-Mortlock and Boardman (1995)[1]	UK South Downs	2×CO_2 climate scenario WXGEN[2] EPIC[3]	Rainfall amount temperature	+150%
Farvis-Mortlock and Guerra (1999)	Mato Grosso, Brazil	HADCM2[5] WEPP[4]	Precipitation temperature CO_2	Annual mean: +27%
Nicks (1993)	USA, 69 sites	2×CO_2 climate scenario CLIGEN[2]	Mean temperature Rainfall amount and frequency	+10.7 to 83.9%
Pruski and Nearing (2002b)	Various sites in the USA	WEPP	Rainfall amount and intensity	+0.85 to 2.38% per +1% precipitation
Savabi and Stockle (2001)	Indiana, USA	WEPP	Temperature vegetation growth CO_2	Down to −5.5%
Michael et al. (2005)	Saxony, Germany	ECHAM4-OPYC3[5] EROSION 2D[6]	Precipitation intensities/extreme weather events	+22 to 66%
O'Neal et al. (2005)	Midwestern USA, 11 sites	HadCM3-Ggal[5] CLIGEN WEPP-CO2	Precipitation, temperature, soil cover, adaptive management	+10 to 274%
Zhang and Nearing (2005)	El Reno, Oklahoma, USA	HadCM3[5] CLIGEN WEPP	Precipitation, temperature, tillage systems, crop growth	+18 to 30%

Pruski and Nearing (2002b) extended their research on the sensitivity of erosion processes to changes in rainfall (as quoted in Table 1) by using a modified version of the WEPP model to include the impacts of climate change on plant biomass production, such as CO_2 fertilization, and changes in soil moisture and solar radiation (Pruski and Nearing, 2002a). Based on this method and climate simulations of the HadCM3 model, the following qualitative conclusions on the impact of climate change on soil erosion were drawn: (i) both a change in precipitation amounts and a shift in precipitation intensities are important aspects to consider in predicting future soil loss; (ii) significant precipitation increases are likely to increase soil losses at disproportional higher rates; (iii) soil erosion rates are more sensitive to runoff than to biomass production. Nearing (2001) investigated the impact of climate change on rainfall characteristics related to their ability to cause soil particle detachment and transport (rainfall erosivity). The author used the output of global circulation models (GCMs) and statistical relationships on erosivity values from the RUSLE model to compute climate change induced alterations of the erosive power of rainfall in the USA. Despite certain inconsistencies, the results showed critical changes in rainfall erosivity of up to 58% at some locations, which may considerably affect future soil erosion rates. Walling and Webb (1996) suggested on basis of empirical data from the Dnestr River in Ukraine that climate forcing already affected soil erosion rates on local scale. The study analysed historical land-use data from the catchment area and attributed a recorded five-fold increase in sediment loads carried by the river since the 1950s in part to major land-use changes, such as forest clearances, but more importantly to observed climatic changes.

In central Europe, especially the cultivation of root crops, such as potatoes, carrots and sugar beet is often associated with a high risk of severe soil losses by water (e.g. Jones et al., 2003). This is accounted for by the coincidence of two factors: ground and canopy cover are low during the time of seedbed preparation and in the first weeks of vegetative development, and secondly this period concurs with the time of the year showing the highest amount of erosive rainfall (Strauss et al., 1995).

There is a large toolbox of soil conservation measures (e.g. Hudson, 1995; Morgan, 2005). One such measure is conservation agriculture, which seeks to avoid unsustainable soil losses while maintaining stable yields. Common approaches include reduced tillage and no-tillage systems, often combined with intercrop cultivation and mulching, to preserve the natural soil structure and a vegetative soil surface cover (e.g. Cannell and Hawes, 1994; Tebrügge and Düring, 1999). Maintaining a soil cover by utilising post-harvest residues or living vegetation to protect soil surfaces from raindrop impact is particularly important to limit soil erosion (e.g. Pimentel et al., 1993; Rose, 1994; Stocking, 1994).

The potential impacts of climate change on European agriculture have been the focus of a number of studies. For example Downing et al. (2000) compiled a broad collection of impact studies on the effects of CO_2 fertilization, temperature variability and precipitation changes on plant growth, crop yields, nutrient cycling and pest infestation. Also the process of

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soil erosion and its consequences have been extensively studied in recent decades (e.g. Wischmeier and Smith, 1978; Julien, 1995; Summer et al., 1998) and the complex role of soil resources in agriculture under a changing climate have been recognized in various publications (e.g. Rosenzweig and Hillel, 1998; Frisvold and Kuhn, 1999). However, studies on the possible impact of climate change on erosion rates are rare and in particular for Central Europe such studies are indeed very scarce (Table 1).

The aim of this case study is to estimate the impact of climate change induced variations in seasonal rainfall pattern on soil erosion rates in the pre-alpine region (Alpenvorland) of Upper-Austria (Oberösterreich), Europe. The specific study objectives are:

- To contribute to filling the gap of climate change impact studies on soil erosion by providing a case study for an agricultural area in Central Europe.
- To assess the influence of land-use management strategies compared to the impacts of seasonal changes in precipitation in this specific case, and to evaluate, if improved land-use management can offset these impacts.
- To test a methodology for a rapid evaluation of the potential impact of seasonal rainfall variations on soil erosion rates on a local scale.
- To provide regional policy makers with additional information for policy development in the agricultural and environmental sector.

2. Methodology

The impact of climate change induced variations in seasonal rainfall pattern on soil erosion rates in the Central European agricultural sector was assessed by means of a modelling case study on sugar beet (*beta vulgaris*) cultivation in Upper-Austria. Selected environmental, agricultural and climatic baseline conditions refer to a research project, which was carried out by Kunisch et al. (1995) in this region to determine soil losses from experimental plots with consideration of different agricultural practices.

2.1. The study region

Summer et al. (1998) documented a 32% increase in sediment yields over the last 40 years in the Austrian part of the Danube river basin and agriculture was identified as the major cause for soil erosion in the catchment area. The federal province of Upper-Austria is part of an agriculturally intensive central European region located north of the Alps. Nearly 50% of its total surface is classified as agricultural land. Fig. 1 shows the geographical distribution of crops with a high soil erosion risk in Austria (Strauss and Klaghofer, 2006). The study area is located within this zone of crops with high erosion risk.

The Alpenvorland has an altitude reaching from 200 m to 850 m above sea level (asl.). Mean annual precipitation is approximately 1000 mm and the average temperature is between 6 and 8 °C depending on the altitude (OOE-GV, 2005). The number of rain days is 127–135 per year (Hydrographischer Dienst in Österreich, 1994).

The main cultivated crops in Upper-Austria are cereals, maize, oilseeds, forage crops, potatoes and beets (Landesregierung Oberösterreich, 2003). In this study we focus on sugar beet as it is a typical example of the erosion sensitive root crop farming in the region. Common tillage practices in sugar beet cultivation include the use of cultivators (ripper) and mouldboard ploughs in autumn for weed control, to prevent soil

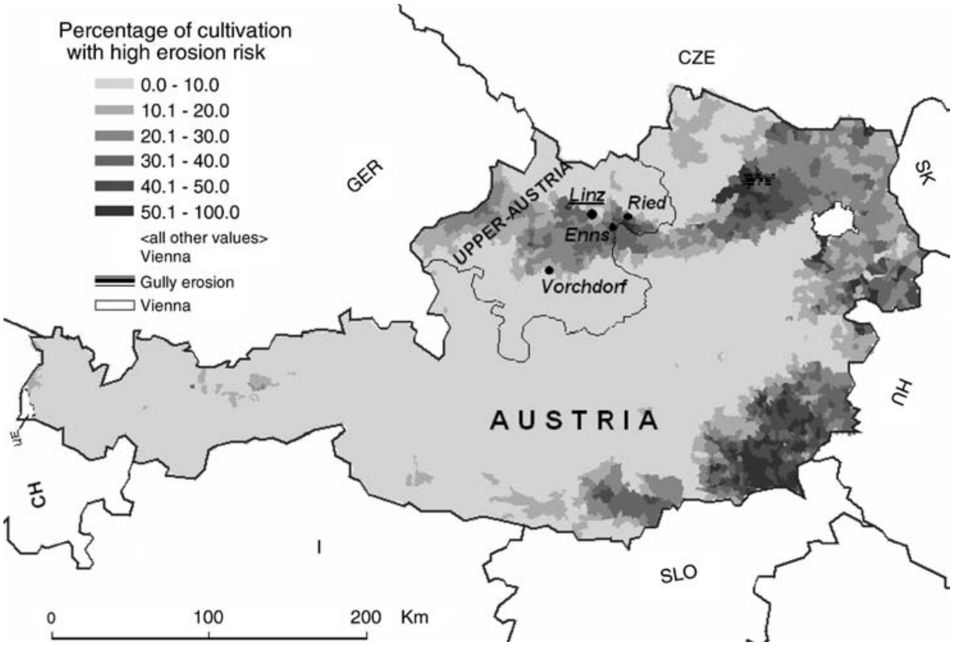

Fig. 1. Geographical distribution of crops with a high erosion risk in Austria. The federal province of Upper-Austria is highlighted showing that the study region Alpenvorland and the locations of experimental plots Enns and Ried belong to the most erosion sensitive areas of Austria (Strauss and Klaghofer, 2006).

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compaction and to quickly incorporate fertilizers and the crop residues. The sugar beet seedbed is prepared in spring with two tillage operations using combinations of different types of harrows. These practices do not include any particular measures to prevent water erosion in the most critical period of the year during spring and early summer.

2.2. The reference study

Kunisch et al. (1995) researched the effect of different sugar beet cultivation practices on soil erosion between 1992 and 1995 in the Alpenvorland region. The project was carried out on three sites in close proximity to each other. Two of them were in the district Enns and one in the district Ried/Riedmark in Upper-Austria. Study sites needed to change because sugar beet is not cultivated in subsequent years on the same plot. Nevertheless cultivation practice and employed equipment were kept constant over the period of the experiment and soil properties differed just slightly between locations as presented in Table 2.

Four different tillage systems for the cultivation of sugar beet were analysed with respect to runoff production and sediment transport. The agricultural year began after the harvest of barley (*Hordeum*) or winter wheat (*Triticum*). This was followed by the preparation of experimental plots either by conventional ploughing or by cultivation of intercrops. Sugar beet was sown in April and harvested after approximately 5 months. The complete agricultural year in this cultivation system comprises a period of 13 months from seedbed preparation for intercrops until sugar beet is harvested. This means that the month September occurs twice in the agricultural year, but is has not been double-counted as it is used first under conditions of seedbed preparation and later under harvest conditions. This time frame has been chosen to take all erosion relevant periods under sugar beet cultivation into account and is maintained throughout this study. It is however only a partial analysis of the agricultural practice, which normally involves different crops over two or more years on each plot. Unfortunately, the available data set did not provide erosion data for entire rotation cycles.

Table 2
Important soil physical properties and related hydrological characteristics of the experimental plots at study locations Enns and Ried in High Austria (BMLF, 1972, 1982)

Soil Properties of Experimental Plots	Qualitative description of soil characteristics	
	Enns	Ried/Riedmark
Type	Brown earth, gley	Brown earth, partly colluvial
pH	Neutral to weakly acidic	Strong acidic
Infiltration capacity	Low	Medium
Water storage capacity	Medium	Medium
Organic matter content	Medium	Low to medium
Workability aspects	Clods form when water is logged	Occasional surface sealing
Agricultural quality	High	High
Soil texture of horizons	A (20–30) cm: Slit, loamy silt BP (55–70 cm): Loamy silt, silty loam or loam S (100 cm): Loamy silt, silty loam, loam	A, AB (10–15 cm, 30–45 cm): Loamy sand or sandy loam B1, B2 (50–65 cm, 90–110 cm): Sandy loam, loam or silty loam B3 (120 cm): Silt, sandy loam, loamy silt, or silty loam

The four cultivation practices on the experimental plots are described as follows: For conventional tillage (PT) a mouldboard plough was used in late August after harvesting the preceding crop to break up the soil for incorporating mineral and organic fertilizers and to improve soil physical properties. The plots were ploughed again in November to create a stable furrow over the winter, which prevented soil erosion to a large extent. In April a rotary harrow trailing a tooth packer roller was used for seedbed preparation directly before sugar beet was drilled.

In the reduced tillage with intercrops (RTI) treatment, the experimental plots were ploughed just once after harvest, followed by seedbed preparation using a rotary harrow. Intercrop species such as Mustard (*Sinapis alba* L.) and Phacelia (*Phacelia tanacetifolia*) as monocultures or as a mixture of Phacelia, Buckwheat (*Fagopyrum esculentum*), Persian Clover (*Trifolium resupinatum*) and Common Vetch (*Vicia sativa*) were then planted. These species are usually killed by frost in January and the residues create a nearly complete soil cover. A flail mower was applied in February to cut the plant residues for mulching. It was necessary to spray a non-selective herbicide a few days before sugar beet was drilled in order to reduce competition by weed growth. The sugar beet seedbed was prepared as for PT.

The conservation tillage with intercrops and mulching (CTIM) and no-tillage with intercrops and mulch (NTIM) used a subsoiler in combination with a rotary harrow for intercrop seedbed preparation in autumn. In spring a flail mower and non-selective herbicides were applied in both systems to prepare the intercrop residues for sugar beet cultivation. The only difference between the two systems was that under NTIM the sugar beet was drilled without seedbed preparation directly into the mulch, while in CTIM a seedbed was prepared by harrowing the plots or by using a rotary cultivator. Table 3 summarizes the major tillage operations in the four cultivation systems, which potentially affect the soil's vulnerability to erosion.

The experimental set-up in this reference study consisted of 12 adjacent plots of 16 m^2 created in a horizontal line. Erosion traps collected sediment and runoff during the erosion sensitive periods of intercrop cultivation from August to October and during the growing season of sugar beet from April to September. Additionally, some rainfall simulation experiments were undertaken in April 1993 and April/May 1995 and September 1995. Runoff and sediment yield were measured during simulated extreme precipitation events of 35–45 mm with an intensity of 60 mm h^{-1} in all four tillage systems on smaller 12 m^2 plots.

Compared to the PT average sediment yields in RTI diminished by 69%, CTIM led to a decrease in erosion of

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Table 3
Agricultural calendar for the four tillage systems

Agricultural calendar	Major tillage operations affecting ground cover			
	PT	RTI	NTIM	CTIM
September	Ploughing	Ploughing and harrowing	Harrow and subsoil tiller	Harrow and subsoil tiller
September	–	Intercrop sowing	Intercrop sowing	Intercrop sowing
November	Ploughing	–	–	–
February	–	Cutting of intercrop	Cutting of intercrop	Cutting of intercrop
Mid-April	Seedbed preparation/ drilling	Seedbed preparation/ drilling	Seedbed preparation/ drilling	Direct drilling
September	Harvest	Harvest	Harvest	Harvest

93%; and NTIM reduced sediment loss by 98%. A substantial difference between different intercrop species in terms of soil protection could not be identified (Strauss and Schmid, 2004). Therefore no specific intercrop species was selected for this study and the chosen vegetation parameter values refer to common intercrops species of similar vegetative development, such as Mustard, Phacelia and Alfalfa (see section on parameter selection).

The data gathered in the described experiments were used for the calibration of the erosion model used in this study. Furthermore the same set of tillage systems and an identical agricultural calendar were applied to the climate scenarios generated for the erosion model runs. Table 4 provides an overview on the dataset produced by Kunisch et al. (1995).

2.3. *The revised Morgan–Morgan–Finney soil erosion model — a modified version*

The Morgan–Morgan–Finney (MMF) model is a simple erosion model based on empirical relations for predicting annual soil loss from field-sized areas on hill-slopes (Morgan et al., 1984). Morgan et al. (1984) tried to retain the practicality of USLE (Universal Soil Loss Equation) in this model, but incorporated some of the more recent advances in the research on soil erosion processes to strengthen the physical basis of the model. The model was extensively validated using erosion plot data and successfully applied by researchers working in wide range of biophysical environments. In 2001, Morgan revised the model and refined the description of the erosion processes and improved its ease of use in terms of parameter selection. No fundamental changes in the model settings resulted from these adjustments. However, the revised MMF model can now also be applied to small catchments as successfully demonstrated by Morgan (2001) in the repeated and extended validation.

The MMF model separates the erosion process into a sediment phase and a water phase. In the water phase, the kinetic energy of rainfall and amount of runoff are calculated. The sediment phase of the model applies these terms to compute the mass of soil detached by rain splash and runoff wash, which sum up to the total amount of soil detached during a precipitation event. Furthermore, the sediment transport capacity of the overland flow is calculated. Soil loss is determined by comparing soil detachment and runoff transport capacity by treating them both as limiting factors in the soil erosion process. Results on erosion rates in the MMF model are in the case of transport limitation most sensitive to soil parameters and to annual rainfall. Whilst detachment limited, model results are most responsive to annual rainfall and average daily precipitation (Morgan, 2005).

The revised MMF model uses a set of 15 input parameters, which describe soil, rainfall, vegetation, and land-use management (Morgan, 2005). These parameters are applied as annual averages to allow the estimation of soil loss per year during a single time-step calculation. This process constitutes a major simplification in the model and significantly limits its applicability for this study. Recalling the study's objective of estimating soil erosion rates under climate change and bearing in mind that significant changes in precipitation pattern are likely to be seasonal, an adaptation of the model was necessary. The introduction of an adequate temporal resolution to the model run was therefore realized achieving a proper reflection of the impacts of intra-annual precipitation changes in the results.

Most sections of the model algorithm remain unaffected by changing soil and vegetation parameters from annual averages to monthly values (Table 5). However the computation of the runoff had to be altered, since the parameter annual rainfall is

Table 4
Summary of the dataset on erosion measurements for Upper-Austria used in this study

The applied dataset on erosion events: records of precipitation events and erosion measurements						
Recording period	No. of precipitation events	No. of erosive rain events	Number of erosion measurements	Max. precipitation [mm]	Max. soil loss per event — conservation tillage [kg/m^2]	Max. soil loss per event — conventional tillage [kg/m^2]
1992[a]	8	3	14	36	1.44	0.01
1993	31	17	78	51	0.49	0.9
1994	58	8	26	70	0.07	0.33
1995	56	6	47	44	0.2	0.79
Rainfall simulator experiments	3	3	26	35–45	1.69	2.83

Only the precipitation events in the respective years are included, during which the erosion traps on the 12 plots were installed. The number of erosion measurements is the aggregated number over all plots under observation.

[a] Autumn only.

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Table 5
The algorithm of the revised MMF erosion model including the modification of the runoff estimation in the water phase (Morgan, 2001; USDA, 2002)

Erosion model algorithm	Equations, parameters and variables of the modified MMF erosion model	
	Equations	Parameter/Variables
Water phase		
(1)	$ER = R \times (1 - A)$	*ER* — effective rainfall [mm]
(2)	$LD = ER \times CC$	*R* — daily rainfall [mm] *A* — interception coefficient [0–1]
(3)	$DT = ER - LD$	*LD* — leaf drainage [mm]
(4)	$KE(DT) = DT(8.95 + 844 \log I)$	*CC* — canopy cover [0–1]
(5)	$KE(LD) = LD((15.8 - PH^{0.5}) - 5.87)$	*DT* — direct throughfall [mm] *KE* — kinetic energy [J m^{-2}]
(6)	$KE_{tot} = KE(DT) + KE(LD)$	*I* — typical intensity of erosive rain [mm h^{-1}]
(7)	$MR = \frac{1000}{CN} - 10$	*PH* — plant height [m] *MR* — potential maximum retention [mm]
(8)	$Q = \frac{(R - (0.2MR))^2}{(R + 0.8MR)}$	*CN* — curve number (1–100) *Q* — runoff [mm]
Sediment phase		
(9)	$F = K \times KE_{tot} \times 10^{-3}$	*F* — soil detachment by raindrop impact [kg m^{-2}] *K* — soil detachability index [g J^{-1}]
(10)	$H = ZQ^{1.5} \sin S(1 - GC) \times 10^{-3}$	*H* — soil detachment by runoff [kg m^{-2}]
(11)	$Z = \frac{1}{(0.5 \times COH)}$	*S* — slope steepness [°] radiant *GC* — ground cover [0—1]
(12)	$J = F + H$	*Z* — resistance of soil [kPa^{-1}] *COH* — cohesion of surface soil [kPa]
(13)	$G = CQ^2 \sin S \times 10^{-3}$	*J* — total soil detachment [kg m^{-2}]
(14)	$E = \min(J, G)$	*T* — runoff transport capacity [kg m^{-2}] *E* — soil loss [kg m^{-2}]

used in the respective equations of the MMF model and the relationship between it and runoff is non-linear. A simple fragmentation of that term into smaller time-steps was not possible. Instead, the runoff calculation method of the revised MMF model was replaced with the Soil Conservation Service (SCS) curve number (*CN*) technique (Table 5, Eqs. (7) and (8)) (Mockus, 1972). The SCS method has been used in a variety of erosion models such as EPIC or CREAMS (Chemicals, Runoff and Erosion from Agricultural Management Systems) and is well established as a simple tool to calculate runoff from rainfall in hydrologic engineering and environmental impact assessments (Ponce and Hawkins, 1996).

The exchange of Morgan's runoff calculation methods with the SCS method allows the use of daily precipitation time-steps instead of annual time-steps. Additionally, the total number of input parameters is reduced from 15 to 11. The parameters ignored in the modified model version are annual rainfall (R_a), the ratio of actual to potential evapotranspiration (E_t/E_o) and the soil parameters bulk density (BD), soil moisture content (SM) and effective hydrological depth (EHD). These parameters, with exception of annual rainfall, are difficult to determine without extensive field measurements and therefore often used for the calibration of the revised MMF model, when field data are absent. Those parameters being important to represent soil hydrological properties (BD, SM, EHD) are summarized in the curve number (*CN*) of the SCS method (Mockus, 1972).

2.4. Parameter selection

The model algorithm requires information on a number of parameters, which needs to be acquired through field research or from empirical data sets. In this study, data were taken from various empirical sources, including general values suggested by Morgan (2001, 2005). These values were adapted as precisely as possible to the local conditions in Upper-Austria using the study of Kunisch et al. (1995). Vegetation parameters were selected from various sources (Table 6). Data on intercrop species were obtained from studies on Phacelia, Mustard and Alfalfa. The vegetative development of these species is similar and minor variations do not cause any noticeable influence on the modelled erosion rates.

The crop management factor (C) in the MMF model is a factor equal to the product of C (crop/vegetation and management) and P (erosion control practice) of the Universal Soil Loss Equation (Morgan, 2001). Factor C in the MMF model is a significant term in the calculation of runoff transport capacity. Here, C was used as a calibration term, because few sources exist that suggest values for C as it is defined for the MMF model. For months with insufficient records for a sound calibration, C was calculated after a method by Schwertmann et al. (1987) based on empirical data gathered in Bavaria, Germany. Schwertmann et al. (1987) provide detailed data for the relative soil loss from various crop rotations dependent on farming techniques and cultivation periods over the year compared to the potential soil loss from uncultivated, ploughed fallow land (Schwarzbrache). C values are obtained by combining the relative soil loss factor of the studied crop with a area-specific values for the relative amount of erosive rainfall occurring in a specified period of time. Typically, C values

Table 6
Ranges of vegetation parameters over the agricultural year in different tillage systems

Vegetation parameter ranges over the year and parameter sources					
Parameter	PT	RTI	NTIM	CTIM	Source
A [0–1]	0–0.15	0.1–0.2	0.1–0.2	0.1–0.2	Morgan (2005), Hoyningen-Huene (1983)
PH [m]	0–0.6	0.01–0.5	0.01–0.5	0.01–0.5	CPIDS [a] Kaffka (2001)
CC [0–1]	0–0.95	0.1–0.95	0.1–0.95	0.1–0.95	CPIDS [a]; Jensen and Spliid (2003), Schmidt et al. (1996)
GC [0–1]	0–0.15	0.03–0.08	0.42–0.8	0.42–0.8	Shelton et al. (1995), Schmidt et al. (1996)

[a] CPIDS — Crop Parameter Intelligent Database System from the National Soil Erosion Research Laboratory (NSERL), Purdue University, USA. (USDA, 2005).

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differ widely between crops, cultivation techniques and different cultivation periods (Schwertmann et al., 1987). Since Bavaria and the study region Upper-Austria are geographically proximate and cultivation techniques are generally similar, the method and input variables by Schwertmann et al. (1987) provide satisfactorily close estimates of C values used in this study. For some months the C values were slightly modified in the calibration process to improve the performance of the erosion model (see below).

The input values for the soil parameters in the erosion model were selected according to suggestions by Morgan (Morgan et al., 1998; Morgan, 2001). The soil detachment index (K) was fixed at 0.9 g J^{-1} and the value for cohesion of surface soil (*COH*) at 3 kPa. These values correspond to those recommended for silt loam soils, which are reasonable representations for the brown earth soils of the experimental plots. The typical intensity for erosive rain (*I*) for the region is best approximated by a value of 10 mm h^{-1} (Morgan, 2001). These parameters were kept constant in the model application. A slope steepness (*S*) of 15° and was chosen to reflect the conditions in the experimental plots studied by Kunisch et al. (1995) representing typical cultivation areas in Upper-Austria.

Soil parameters were treated as being constant across all tillage systems as well as over time with the exception of *CN* (Table 7). The curve number (*CN*) value in the SCS method for runoff estimation is used for computing the soil's potential maximum retention of rainfall water, which depends mainly on the infiltration properties of the soil and on its surface storage capacity (USDA, 2002). Seasonal variations of the *CN* value relate to the hydrological effects of tillage operations and vegetation cover. Since the SCS method is mainly applied in the USA, soils in Europe have not been consistently classified into any of the hydrological soil groups being used for the determination of *CN*. The soils in the study region of Upper-Austria have hydrological features that correspond to the soil groups B or C of the SCS method, which are characterised by having a slow to moderate rate of water transmission (Mockus, 1969). This served as a starting point for the determination of *CN* in the calibration process. Relevant seasonal changes of runoff behaviour caused by tillage operations were included through this factor into the modelling process.

2.5. Calibration of the erosion model

The modified version of the revised MMF erosion model was calibrated with precipitation and erosion data from experimental plots cropped with sugar beet and various intercrop species in Upper-Austria. The parameters to be calibrated were *CN* representing soil hydrological properties and the crop cover management factor C. Table 7 gives the ranges and annual average values of *CN* and C, which resulted from the model calibration and from supplementary calculations of *C* using the method of Schwertmann et al. (1987). The averaged *C* factors in the different tillage systems correspond sufficiently well to values estimated by Morgan (2005) and Schmidt et al. (1996). The calibration of the erosion model through the C and *CN* values has the function to effectively absorb the imprecision resulting from generalized soil and vegetation parameters chosen from literature. Thereby the local conditions determining soil erosion through water are better reproduced and model performance is improved, even though the specific C and *CN* values occasionally appear to be slightly outside the conventional range normally quoted in the literature in RUSLE and the MMF model.

Fig. 2 shows that the erosion model captures the response of the PT and CTIM treatments to increases in precipitation, which is also true for the other treatments not represented in the figure. Model performance in all other tillage systems improves for precipitation events between 20 and 35 mm.

Testing the model against the results of rainfall simulator experiments of Kunisch et al. (1995) showed that the model underestimates erosion rates during extreme rainfalls. The simulated events of 35–45 mm rainfall with an intensity of 60 mm h^{-1} resulted in soil losses for PT, RTIM and CTIM systems that exceed the model predictions by a factor 6.0 to 7.3. Conversely NTIM showed higher values in the soil loss prediction than actually measured. However, extreme events of >35 mm rainfall per day are rare in the study region. At Vorchdorf meteorological station an annual average of 1.44 rainfall events exceeded 35 mm between 1975 and 2001. Local rainfall intensities are usually below 60 mm h^{-1}, which means soil losses during >35 mm events are likely to be on average lower than measured in the high intensity rainfall simulator experiments. This is likely to reduce the error for >35 mm precipitation events below the factor 6.0 to 7.3, but nevertheless the model's underestimation of soil loss rates during extreme rainfall events persists and is likely to cause a systematic error in the results. This will be discussed below together with other sources of uncertainty relevant to this study.

The model performs reasonably well for the range of precipitation events up to 35 mm, which comprise about 98% of the potentially erosion relevant rainfall events over the year. In this range of rainfall events, the measured average erosion rates are accurately reproduced and also the effect of different agricultural practices on soil loss is adequately reflected. A statistical evaluation of the calibrated model against field data measured in May and June is given in Table 8. Measured

Table 7
Ranges and annual averages of the calibration terms *C* and *CN* in the different tillage systems

C-factor and *CN* in the revised MMF erosion model	Ranges and annual averages (in brackets) in different tillage systems			
	PT	RTI	NTIM	CTIM
C-factor	0.01–0.9 (0.25)	0.01–0.52 (0.15)	0.01–0.27 (0.07)	0.01–0.27 (0.06)
CN	55–93 (71)	75–82 (78)	65–70 (68)	60 (60)

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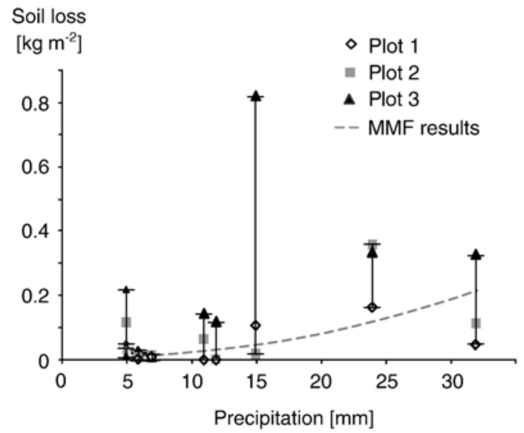
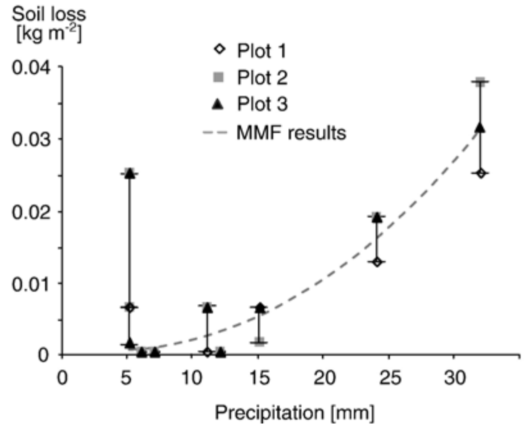


(a) PT - May



(b) CTIM - May

Fig. 2. Model behavior after the calibrating it with the dataset of Kunisch et al. (1995) for the (a) PT and (b) CTIM treatment. In both cases three measurements of each precipitation event give a range soil erosion data. Each measurement was gained on a different plot. All three plots have been cultivated using exactly the same tillage operations. The dashed trendline describes the model behaviour.

sediment yields of single rainfall events were compared against the model predictions (as graphically demonstrated in Fig. 2) and resulting differences are expressed by the statistical χ^2 distribution and the corresponding probabilities. A value close to 1 describes a high accuracy of model predictions.

2.6. Weather data for climate change impact studies

The assessment of regional and local climate change, which is essential for the precise estimation of impacts and for the development of specific response strategies, is difficult using the output of coupled global circulations models (GCMs). Many factors influencing regional climate, such as smaller topographic features causing orographic rainfall, are not adequately represented in the coarse horizontal resolution of GCMs, which typically extends to 300 km representing several degrees longitude and latitude in one grid cell (e.g. Benestad and Forland, 2001; Hardy, 2003; Houghton, 2004). Finer grid resolutions are not yet possible because of the complexity of the climatic system, the vast number of feedback reactions and the current computational limitations (Harvey, 2000; Houghton, 2004). One approach to overcome this deficiency is the use of regional climate models (RCMs). These models use GCM output at their boundaries to simulate climate at a higher resolution for a limited geographical area (Wilby and Wigley, 1997; Carter, 2001). RCMs numerically represent the atmosphere and land surfaces for simulating the important aspects of the climatic system as relevant for impact studies, such as radiation, rainfall and soil hydrology (PRECIS, 2004). RCMs are able to provide the high-resolution of climatic changes on the temporal and spatial scales, needed to conduct sound regional impact studies.

The precipitation data for the climate change scenario in this study is based on results of the model HadRM3H, which is the most recent RCM from the Hadley Centre for Climate Prediction and Research, UK. HadRM3H is limited to the European area and has a horizontal resolution of 0.5° × 0.5° longitude, latitude respectively, and 19 atmospheric and four soil levels. It also includes a sub-model of the sulphur cycle to estimate the cooling effect of sulphate aerosols from SO_2 emissions (PRECIS, 2004). Boundary conditions for HadRM3H are provided by HadAM3, which is the atmospheric component of HadCM3, the latest coupled atmospheric and oceanic GCM of the Hadley Centre (PRECIS, 2004; PRUDENCE, 2004).

Results of two HadRM3H runs were used to create (i) a climate change scenario with altered seasonal rainfall pattern and (ii) a reference scenario, which represents the rainfall pattern in an undisturbed climate serving as baseline. The reference scenario comprises the period 1960–1989 and the climate change model run is based on the SRES emission scenario A2 for the years 2070–2099. The A2 emission scenario storyline assumes a heterogeneous world where the preservation of local identities is emphasised. Global population increases steadily, economic growth and technological change are fragmented and comparatively slow, whilst climate change relevant gases continue to be emitted at high rates (IPCC, 2000).

Daily precipitation data for the climate change scenario (2070–99) and the baseline period (1960–89) were generated with the stochastic weather generator of the Long Ashton Research Station (LARS WG 3.0) (Semenov and Barrow,

Table 8
The results of statistical tests on MMF erosion model performance for the months May and June are given in this table

Statistical test of model performance after calibration		Model performance in different tillage systems			
		PT	RTI	NTIM	CTIM
May 10 degrees of freedom	χ^2-value	1.69	2.21	6.48	10.78
	Probability	0.99	0.99	0.77	0.37
June 11 degrees of freedom	χ^2–value	7.92	3.63	1.83	2.00
	Probability	0.72	0.98	0.99	0.99

The model behaviour is satisfactory for these precipitation intensive periods, considering the high number of changing vegetation parameters in the early growing stage of sugar beet.

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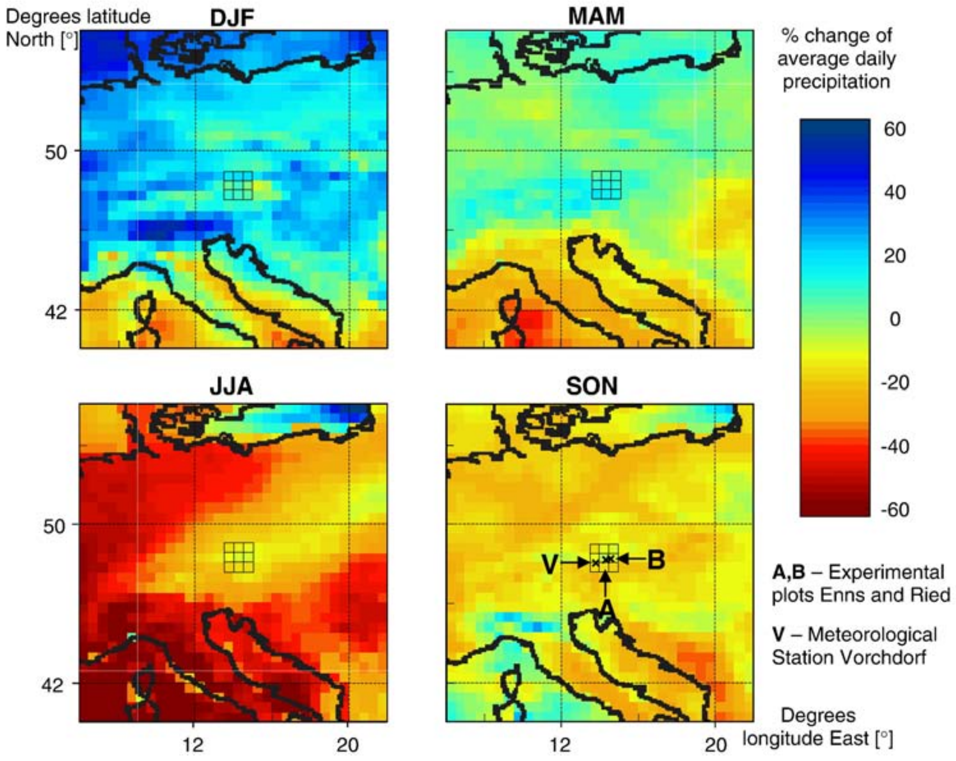

Fig. 3. Relative changes of seasonal precipitation quantities in Central Europe. The data refer to the SRES A2 scenario and compare a climate change run (2070–99) with a 1960–89 control run of the regional climate model HadRM3H. The 3 × 3 grid in the seasonal panes shows the area, over which the climate data have been averaged. The crosses in the SON pane mark the locations of experimental p lots in Enns (A) and Ried (B), and the Meteorological Station Vorchdorf (V).

2002). LARS WG was developed to produce artificial time series of weather data for hydrological and agricultural studies and for climate change impact assessments (Semenov and Barrow, 2002). A series of wet and dry days, daily precipitation and solar radiation is simulated by means of semi-empirical distributions, which are derived from statistical characteristics of observed weather at a particular location (Barrow and Lee, 2000). Data for daily minimum and maximum temperatures are generated stochastically on the basis of daily mean temperatures and standard deviations dependent on the day being either wet or dry (Semenov and Barrow, 2002). The location specific climate parameters gained in the calibration process of LARS WG were perturbed with results of the HadRM3H runs. Thereby, daily weather data were generated for local climate change scenarios (Semenov and Barrow, 2002). Model verification is undertaken by comparing the statistics of a synthetic data set with the weather records used in the model calibration (Barrow and Lee, 2000).

2.7. Climate change and baseline scenario weather data

The described HadRM3H simulations of the IPCC SRES A2 scenario (2070–99) and the corresponding control run (1960–89) provided the information on the magnitude of change in the considered climate parameters in the study region. Seasonal precipitation changes (Fig. 3), temperature changes and the standard deviation of mean temperatures have been computed based on these model runs (Table 9).

To reduce the bias of single grid cell values in the simulation an arithmetic average over 1.5° × 1.5° longitude and respectively latitude was calculated. This 3 × 3 grid cell pane includes the locations where experimental plots were set up for the study of Kunisch et al. (1995), which was used to calibrate the erosion model, and the meteorological station Vorchdorf, which provided the records to calibrate the weather generator LARS WG.

Table 9 gives the results of HadRM3H climate simulation runs, which describe a strong uniform increase in temperature and rather moderate change in annual precipitation for the period 2070–99 compared to 1960–89. A precipitation decrease over summer (JJA) and autumn (SON) and an increase in spring (MAM) and winter (DJF) constitute a significant shift within the intra-annual precipitation pattern although the percent change in annual precipitation (−2.51%) is small.

2.8. Calibration of the weather generator and production of time series rainfall data

The weather generator LARS WG was calibrated with a data set from the Meteorological Station Vorchdorf, which lies approximately 50 km south-west of the experimental plots A and B. The calibration data comprise complete records of precipitation and temperature from 1975 to 2001 in daily time-steps. From this data set semi-empirical distribution of rain amounts and rain-day and dry-day series were derived. Based on these, synthetic weather data were generated and statistically

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Table 9
Seasonal average changes in precipitation, temperature and standard deviation of temperature

SRES A2 Climate Change Scenario of HadRM3H	Changes of climatic parameter from 1960–89 to 2070–99			
	Total precipitation [%]	Total precipitation [mm]	Average temperature [°]	Standard deviation temperature [°]
DJF[a]	9.89	17.6	5.09	1.01
MAM[a]	10.81	25.7	4.24	0.93
JJA[a]	−14.62	−55.8	5.58	1.17
SON[a]	−14.53	−35.2	5.55	0.97
Annually[b]	−2.51	−47.7	5.12	1.02

The values are 3×3 grid cell arithmetic averages including all three relevant location of the experimental plots and the meteorological station Vorchdorf.

[a] DJF — December, January, February; MAM — May, April, March; JJA — June, July, August; SON — September, October, November.

[b] Precipitation change is the absolute change over the year and not the arithmetic average of seasonal values.

compared with the records to verify if there were significant differences between the artificial and empirical precipitation distributions. After this validation a 30-year time series of daily weather data was generated, which formed the baseline scenario (1960–89). The results obtained from the HadRM3H model runs were used to perturb the climate parameters used in LARS WG and a second 30-year series of daily weather data was generated, the climate change scenario (2070–99).

LARS WG reproduces the climatic conditions at Vorchdorf satisfactorily with just minor deviations resulting from the stochastic component of the weather generator. Monthly changes in precipitation, as simulated by the regional climate model HadRM3H, are reflected with great accuracy. The difference between perturbation factor and generated change in monthly average precipitation does not exceed 0.6%. Hence, both weather data series of the reference and the climate change scenarios can be seen as adequate accounts of baseline climate and of the current knowledge on future climatic changes as relevant to seasonal rainfall distribution.

Table 10 shows that the average number of annual precipitation events remains constant in the two LARS WG simulated 30-year series of weather data. A slight decrease compared to the Vorchdorf records in classes of low rainfall intensity is evident, but this change is negligible, since lower rainfall intensities have a limited impact on erosion processes.

Records from the experimental plots showed that precipitation events of less than 3 mm are not relevant for erosion processes, thus these rainfalls are not considered in the erosion modelling exercise. Such low intensity rainfalls comprise approximately 45% of the total number of precipitation events (Table 10). Also precipitation events occurring, presumably as snowfall, on days with an average temperature below 0.0 °C are not included into the erosion model runs. Snowmelt erosion is mainly relevant in northern Europe (Jones et al., 2003), consequently it was seen to be unnecessary to integrate an additional sub-model on snowmelt runoff into the erosion model.

3. Results

The calibrated erosion model was applied using two 30-year time-series of rainfall data generated by the LARS WG. All relevant precipitation events are documented in Table 11. One data series represents the climatic baseline condition form 1960 to 1989 and the second series includes the climate change perturbation as simulated by the climate model HadRM3H for 2070 to 2099. While no significant difference in annual precipitation amounts is predicted for the climate change scenario, a seasonal shift of precipitation from summer and autumn to winter and spring months was simulated (Table 9). This shift of precipitation quantities has a clearly observable impact on the soil erosion rates in all four tillage systems.

Table 11 demonstrates a seasonal increase in soil erosion rates in spring (MAM) and winter (DJF) resulting from higher precipitation rates in these seasons (Table 9) under climate change conditions. This increase in soil loss is outweighed by decreasing soil erosion rates in summer (JJA) and autumn (SON) following lower rainfall rates in these periods in the climate change scenario. The net effect of increasing precipitation amounts in spring and winter and lower precipitation amounts in summer and autumn is a lower overall soil erosion rate across all four tillage systems ranging from 10.6% to 24.1% per agricultural year. Independent from the climatic circumstances RTIM reduces soil erosion by about 41%. CTIM achieve reductions of 82% and NTIM 87%. These results are a successful reproduction of the protective effects of conservation tillage systems observed in the original dataset, which range from 55–99% depending on tillage system and cultivated intercrop species (Kunisch et al., 1995).

Fig. 4 clarifies the principal reason for an annual decrease in soil erosion of 10.6% to 24.1% caused by an overall 4.7%

Table 10
The average number of annual precipitation events recorded at Vorchdorf Meterological Station compared to those simulated for the baseline period (1960–89) and the climate change period (2070–99) using the LARS WG

Average Annual Number of Precipitation Events After Daily Intensities [mm day^{-1}]	Number of precipitation events recorded and simulated by LARS WG		
	Events recorded at Vorchdorf Meteorological Station 1975–2001 [a^{-1}]	Events simulated for baseline period 1960–89 [a^{-1}]	Events simulated for climate change period 2070–99 [a^{-1}]
>50.0	0.33	0.47	0.30
35.0–49.9 mm	1.11	1.47	1.17
25.0–34.9 mm	3.19	2.87	2.80
15.0–24.9 mm	10.08	11.57	10.50
10.0–14.9 mm	16.30	16.10	15.97
5.0–9.9 mm	34.41	33.33	33.63
3.0–4.9 mm	26.48	25.12	25.77
0.0–2.9 mm	77.63	75.13	75.93
Total	170.52	166.07	166.07
Average annual precipitation [mm]	1010.0	1016.1	968.4

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Table 11
Simulated average seasonal soil erosion rates over 30 years in different tillage systems for the baseline and climate change scenario

Modelled soil erosion rates	Seasonal soil losses as simulated in both scenarios [t ha^{-1}]								
	Scenario	SON	DJF	MAM	JJA	S	Total	%[a]	%[b]
PT	1960–89	0.50	0.02	3.61	6.88	0.40	**11.4**	**100**	**−10.6**
	2070–99	0.32	0.04	4.55	5.01	0.29	**10.2**	**89.4**	
RTI	1960–89	1.69	0.06	1.43	2.69	0.31	**6.2**	**58.8**	**−18.7**
	2070–99	1.15	0.03	1.83	1.87	0.22	**5.1**	**44.6**	
NTIM	1960–89	0.75	0.01	0.52	0.77	0.02	**2.1**	**18.1**	**−14.3**
	2070–99	0.52	0.03	0.68	0.52	0.02	**1.8**	**15.4**	
CTIM	1960–89	0.60	0.01	0.39	0.57	0.02	**1.6**	**13.9**	**−24.1**
	2070–99	0.39	0.02	0.51	0.38	0.01	**1.3**	**11.6**	
Seasonal precipitation [mm]	1960–89	176.3	233.5	371.3	235.0	176.3	**1016.1**	**100**	**−4.7**
	2070–99	193.9	259.2	315.6	199.7	193.9	968.4	**95.3**	

[a] Difference in soil loss relative to the conventional tillage baseline scenario value (=100).

[b] Percent change between climate scenarios within tillage systems.

reduction in precipitation (Table 11). The major soil losses occurs in months (May, June, July) when intense rainfall coincides with low vegetative soil protection. The main seasonal shift of precipitation amounts simulated by HadRM3H occurs from such erosion sensitive months to a period of small relevance to erosion (e.g. DJF), which is characterized by less erosive rainfalls and higher ground cover. This precipitation shift towards erosion insensitive months causes the net-decrease in soil loss across all tillage systems.

This effect on soil loss becomes even more obvious when looking at the results on monthly time-scale. Approximately 80% of the total annual soil loss has been simulated to occur within four months. In the case of PT this period comprises April, May, June and July. For the conservation agriculture systems RTIM, CTIM and NTIM September is more significant than April in terms of erosion rates, because of the additional seedbed for intercrop cultivation. The strong reduction of summer and autumn precipitation of over 14% outweighs the precipitation increase in spring. The increase of winter precipitation is in this context negligible, because it is small in absolute terms and does not significantly affect erosion rates during DJF.

The most significant seasonal decrease in soil loss coincides with the precipitation reduction in the summer period JJA (Table 11). This reduction in soil erosion (−31.1%) is significantly larger than the precipitation decrease (−14.6%). Since the number of precipitation events of more than 40 mm also decreases significantly from 0.7 to 0.43 (−38.6%) in this period, it can be assumed that the events of heavy rainfall exceeding 40 mm have a dominating impact on total annual soil loss rates. This interpretation points at the predominant problem of the chosen methodology, which does not include frequency changes in extreme precipitation events under climate change due to the inability of GCMs and RCMs to reliably quantify changes in this weather parameter. The role of extreme weather events in relation to the methodology is further discussed below. The results also show that the relative reduction of soil loss in the conservation tillage systems RTIM, CTIM and NTIM is on average 32.4% during JJA and thereby exceeds the decrease simulated for the PT conventional tillage system, which is only 27.2%. From these data some conclusion might be gleaned on the protective properties of mulch in relation to extreme weather events. However, the uncertainty in the model parameterisation causes too much noise in the output signal to allow statistically sound conclusions on specific aspects of single tillage systems, which would depend on such small differences in the modelled erosion rates.

4. Discussion

The results confirm the significance of just few erosion sensitive months in sugar beet cultivation. Peaks in soil loss were identified during the time of seedbed preparation and the early stages of vegetative development, a period coinciding with high precipitation amounts. Annual soil erosion rates under climate change in Upper-Austria are likely to get reduced, because simulated precipitation rates in the climate change scenarios are lower in most of these erosion sensitive months compared to the climate reference scenario. Simulated rainfall amounts increase mainly in months with higher soil surface protection and naturally less erosive rainfall, which results in comparatively minor increases in soil loss.

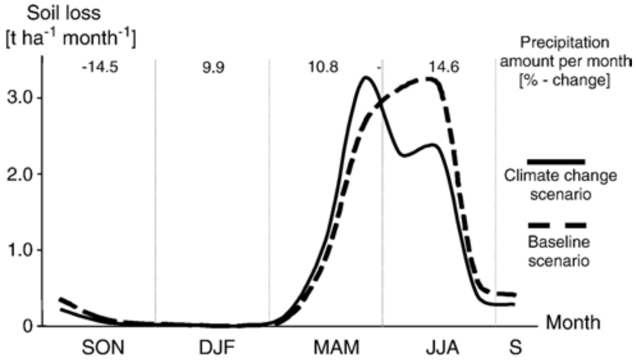

Fig. 4. Total annual soil erosion rates averaged over 30 years in the two scenarios. September is included twice because of the described 13-months agricultural year. Soil loss quantities are set in relation with the loss of soil in the conventional tillage system of the 1960–89 reference period.

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The results contrast with studies conducted for other sites in the UK, USA and Brazil as presented in Table 1. The observed deviation is likely to be explained by significant differences among the predicted character of regional climate change in the various studies, which are reflected in the applied climate change scenarios. For example Botterweg (1994) assumed a climate change scenario for Southern Norway with opposite seasonal precipitation shifts than simulated by HadRM3H for Austria. The scenario applied for Norway predicted a decrease in spring precipitation and an increase of summer and autumn precipitation on balance outweighing the spring decrease. Botterweg (1994) consequently estimated an increasing annual soil loss under climate change conditions. Comparing the two studies, which show contrary results caused by the same phenomenon of intra-annual precipitation shifts in opposite directions, highlights the importance of seasonal precipitation pattern for soil erosion research under climate change. But it also points at the uncertainties in climate change impact research (Table 12), especially in relation to the use GCM and RCM output.

The results of this study are likely to get modified by including other climate change impacts. For example climate change is likely to cause an increase in extreme precipitation events (IPCC, 2001a), which was not considered in the applied methodology. Rainfall simulator studies have shown that single extreme events can results in soil losses on the conventional tilled plots of up to 19.3 t ha^{-1}. Based on the generated weather data, which show an annual average frequency of 1.9 rain events with an intensity of >35 mm in the reference period 1960–89, a 20% increase of such events during the most erosion sensitive months could lift soil losses on average by about 4 t ha^{-1} in the conventional cropping system. This would significantly exceed the erosion reductions gained by seasonal shifts in the precipitation pattern. Other parameters not considered in this study, which are responsive to climatic variability and climate change, are likely to alter the simulated erosion rates further. For example the effect of CO_2 fertilization and higher mean temperatures would favour enhanced plant growth resulting in improved vegetative soil cover. This would have particular significance for sugar beet as it belongs to the category of C_3 plants, which potentially benefit most from increasing atmospheric CO_2 due to their metabolic properties. However, these advantages might be offset by increased water stress for crop plants over the summer period resulting from reduced precipitation amounts. Also higher rates of pest infestation inhibiting plant growth have been predicted, which might result into reduced vegetative soil cover (Parry, 1990; Downing et al., 2000). Downing et al. (2000) documented that these opposed effects often balance each other out and are therefore of minor importance compared to adaptive measures in agricultural management. Soil responses to climate change may also play role in the climate change impact assessment for the agricultural sector (Armstrong et al., 1994). Fig. 5 gives a summary on the most important aspects of the complex climate–soil–plant interactions, which influence soil erosion processes.

Finally wind erosion needs to be considered in the context of climate change and agriculture. Decreasing precipitation amount in summer time leaves soils drier and more susceptible to the erosive forces of strong winds. The IPCC (2001a) stated an increasing frequency of short-duration hazards like windstorms is likely, which will possibly raise total erosion rates in Europe.

Table 12
Sources of uncertainty and estimations about their probable impact on the results

Uncertainty in tools and methods	Specification of uncertain elements		
	Origin	Direction of change	Estimated magnitude
HadCM3/ HadAM3	Incomplete knowledge on atmospheric physics Simplifications in the climatic systems	?	?
HadRM3	Uncertain boundary conditions (HadAM3) Simplifications, still coarse resolution	?	?
SRES A2	Assumptions on socio-economic development Projections on atmospheric GHG concentration	?	Medium
Meteorological Records	Common measuring uncertainties	?	Small
LARS WG	Deficient weather simulation	?	Small
Rainfall intensities	Not explicitly considered	+	High
MMF erosion model	Underestimation of soil loss in extreme events Simplifications in model algorithm	+	Medium
Calibration	Limited quantity of data resources Measuring uncertainties in reference study	?	?
Vegetation parameter	Assumption: vegetative development remains unchanged under climate change	?	Small
Soil parameter	Assumption: soil properties remains unchanged under climate change	?	Small
Curve number (*CN*)	Not measured in the field but estimated and used as calibration variable. Influence of climate change disregarded.	?	?
Land-use management	Adaptive land-use management (e.g. new crops, innovative technology)	–	High

As described in the introduction, the problem of high soil loss rates in root crop farming is well known and extensively described in the literature on soil erosion (e.g. Kainz, 1989; Jones et al., 2003; Morgan, 2005). Soil erosion rates in conventional tillage exceed 10 t ha^{-1} a^{-1} in both climate scenarios. Reduced tillage and presence of intercrops limit these losses to 5 to 6 t ha^{-1} a^{-1}. CTIM and NTIM have been shown to reduce soil erosion by 80 to 90%. The magnitude of these conservation effects corresponds to results gained in various studies on erosion control in root crop cultivation (e.g. Kainz, 1989). However, the estimated erosion rates for conventional and reduced tillage clearly exceed what is described as long-term tolerable soil loss (UNEP, 2002; Jones et al., 2003). The results also show the potential of alternative tillage practices for erosion control and for offsetting adverse changes intra-annual precipitation pattern caused by climate change. The protective effect of vegetative soil cover is likely to prove even more valuable in terms of soil water conservation in a changing climate. As described above, crops are likely to experience higher water stress in climate change scenarios as projected by HadRM3H, when

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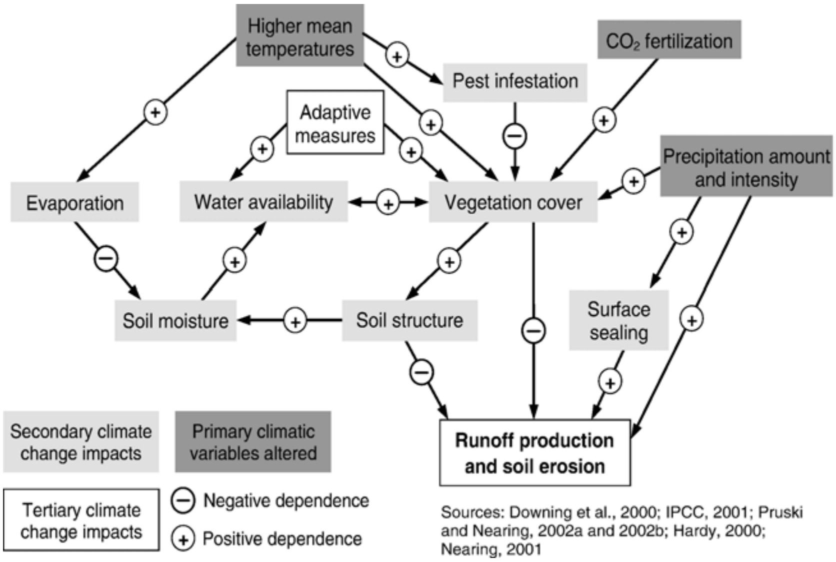

Sources: Downing et al., 2000; IPCC, 2001; Pruski and Nearing, 2002a and 2002b; Hardy, 2000; Nearing, 2001

Fig. 5. Climate change impacts acting on soil erosion processes by water are multifarious and complex. The figure shows in a qualitative way the most important of these interactions and feedback reactions, which depend on regional climate, specific physical, chemical and biological soil properties, vegetation and local land-use regimes. High uncertainties are affiliated with any attempt to predict the direction and the magnitude of change in these parameters. The central role of vegetation cover in erosion control becomes obvious as well as the related difficulties to predict vegetative development under climate change.

temperature increases coincide with decreasing precipitation over the summer months. Assuming such conditions, a mulch cover would decrease the direct evaporation of rainfall water and consequently more water would be retained in the soil being available for crop plants (Fig. 5).

The methodology used in the study shows some limitations, but nevertheless it proved to be an adequate approach for a preliminary assessment of the potential effects of climate change induced variations in seasonal precipitation pattern on soil erosion rates for the selected region. One shortcoming is that the applied climate scenario does not reflect any possible changes in the frequency of extreme precipitation events. The simulated frequency change in >50 mm rainfall, as presented in the results, originates from the perturbation of LARS WG weather parameter and not from a genuine decrease of such events. Another problem is that the impact of varying rainfall intensity is not considered, because LARS WG does not generate break-point rainfall data and the revised and modified MMF does not include precipitation intensity as a variable. Therefore soil losses caused during extreme weather events are not adequately represented by using this method, even though the performance of the model is generally satisfactory with respect to the study objectives.

All climate change impact studies are subjected to considerable uncertainty, which need to be adequately addressed while using the results of this and similar studies for further research and for policy making purposes. Impact studies use a number of tools with inherent uncertainty at various stages causing an unknown error, which propagates through the assessment (Carter, 2001). Even though most climate change models and scenarios are highly sophisticated, systematic and stochastic errors are still abundant. Such errors are caused by a lack of knowledge about the behaviour of certain compartments in the climatic systems, and by incompletely researched and unknown feedback reactions (Santer, 1993). Regional and local studies integrate experimentally obtained knowledge, extrapolations and additional parameters, all exhibiting inherent levels of uncertainty (Puhe and Ulrich, 2001). Some aspects of parameter uncertainty as found in this study have been outlined above and Table 12 summarizes all major sources of possible bias in the results.

Future research, which aims to investigate the impact of climate change on soil erosion, has to reduce the inherent uncertainties outlined in this paper. Important factors to be considered are rainfall intensities, increasing frequency of extreme weather events and the vegetative development of crop plants influenced by various primary and secondary physical, chemical and biological impacts of climate change.

5. Conclusion

The results of this study show a decrease in soil loss from both conventional and conservation tillage systems from 10.6% to 24.1% per agricultural year caused climate change induced seasonal rainfall variations. The decline of erosion rates exceeds the change in precipitation quantity, which is predicted to decrease just slightly in the study region by about 5% under the IPCC climate change scenario SRES A2 scenario (2070–99). This effect can be attributed to a net decrease of precipitation in erosion sensitive months, while precipitation increases in months when agricultural soils used under sugar beet cultivation are less prone to erosion. The computed magnitude of change in soil erosion rates can be considered to lie inside the margins of uncertainty typically attached to climate change impact studies.

The results of this modelling study successfully reproduce the unsustainably high rates of soil loss in conventional sugar beet farming as measured in the field. Also the simulated soil erosion

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rates for the different tillage systems are well reproduced by the revised and modified MMF erosion model and agree with a wide range of studies by estimating a 41 to 87% reduction for three conservation agricultural practices in comparison to the conventional tillage system.

Conservation tillage systems maintain their protective effect on soil resources independent from the applied climate scenario. This indicates the adaptive potential of the agricultural sector for regions where more adverse climate change impacts might occur.

The applied methodology was found to be an adequate approach for a preliminary assessment of the problem soil erosion in a scenario of climate change induced seasonal variations of precipitation pattern. Nevertheless some limitations still exist, primarily with respect to the impact of rainfall intensities and extreme precipitation events. However, the results of this study indicate, despite the uncertainty, that climate change induced seasonal variations in precipitation pattern do not have a major impact on soil erosion in Central Europe in the case of spring sown crops such as sugar beet. This might be considerably different for other crop rotations and tillage practices than those subjected to this study. Hence, further efforts should be directed at deepening the climate change impact research in this field and in assessing and improving the adaptive potential of European agriculture to prevent economic and environmental damage inflicted by a changing climate.

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