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Simulating long-term erosion effects on soil productivity for central Switzerland using the EPIC model

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Abstract The validity of the EPIC (Erosion/Productivity Impact Calculator) model was tested for a site in the undulating ground moraine region of central Switzerland which has uniform soil and relief conditions (silt loam, 10% slope). The EPIC weather generator was used to generate long sequences of synthetic weather with the characteristics of the present-day. Based on these data, soil losses associated with different crop rotations and cultivation techniques for variable initial soil depths were simulated. The results are employed in an economic decision model where the choice of crops, associated with distinct erosion rates, allows the farmer to control soil loss. A first evaluation of the economic model indicates that the financial losses, attributed to soil erosion, are fairly small and hardly influence the long-term optimal behaviour of the farmer. Thus, there is a strong case for intervention by the government provided that society places a high value on the existence of non-eroded soil.

INTRODUCTION

The understanding of soil erosion–productivity relationships is crucial for assessing the extent to which agricultural production is affected by soil losses. The long-term consequences of soil erosion on soil productivity are often not included in an economic evaluation. Empirical studies in North America and Europe showed that crop yields may decrease with decreasing soil depth as a result of long-lasting soil erosion (Battiston *et al.*, 1987; Becher *et al.*, 1985; Swan *et al.*, 1987). Economic calculations, suggesting high financial losses due to the decline of soil productivity (Colacicco *et al.*, 1989), stimulated the development of models for the optimal private and social agricultural utilization of the soil. The availability of economically viable soil conserving investments for a single farmer depends crucially on the perfect divisibility of the investment. Soil loss rate and crop yield reduction vary considerably for different types of crops, thus the choice of the crop itself is a soil conservation strategy open to nearly all farmers. Goetz (1997) presents a theoretical model for the determination of the optimal intertemporal path of soil use when the farmer's crop is mixed and the use of inputs is determined endogenously while accounting for nonlinear relationships within the dynamic process of soil losses.

Within the framework of a new governmental program to financially support sustainable land-use systems in the form of integrated farming or organic agriculture, a Swiss farmer has to consider several quality criteria, such as the "soil protection index" (SPI) which depends mainly on crop rotations and tillage operations (Bundesamt für Landwirtschaft, 1996). One objective of our study is to analyse the efficiency of the SPI with regard to soil erosion control practices. For an area in the undulating ground moraine region of central Switzerland where the eutrophication of several lakes due to soil erosion and other forms of agricultural nonpoint-source pollution is an important environmental issue, long-term (100 years) soil loss rates and crop yields for different cultivation techniques as functions of initial soil depth were calculated using the EPIC (Erosion/Productivity Impact Calculator) model (version 3090); (Sharpley & Williams, 1990; Williams *et al.*, 1990). The results are employed in a dynamic economic model where the choice of crops, each associated with distinct erosion rates, allows the farmer to control soil loss. As a first step, EPIC needed to be calibrated for Swiss conditions and the applicability of the model needed to be verified. These results are reported here.

METHOD AND STUDY SITE

EPIC was originally designed by the US Department of Agriculture for use in the appraisal for the 1985 US Resources Conservation Act (Sharpley & Williams, 1990; Williams *et al.*, 1990). An important aim was to estimate the effect of erosion on long-term soil productivity to provide an accurate tool for agricultural decision-making. Thus EPIC appeared to be the appropriate bio-physical simulation model to generate data to be employed in an economic model (Schmid *et al.*, 1998). Since it

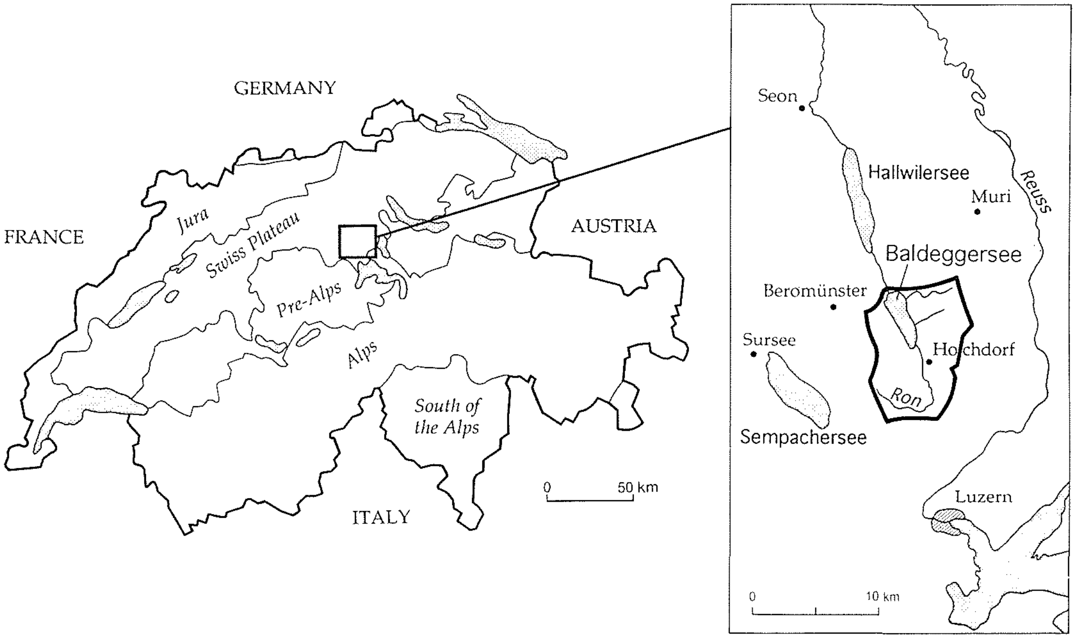

Fig. 1 Location of the Baldegg catchment in the central Swiss Plateau.

Table 1 Soil properties of the test site.

Soil horizon	Depth (m)	Bulk density (g m^{-1})	Coarse fragments (%)	Sand (%)	Silt (%)	pH
Ap	0–0.28	1.4	6	10	82	6.0
Bw	0.28–0.80	1.6	14	7	83	5.9
Bwg	0.80–1.25	1.5	20	6	84	6.2

was the first application of EPIC in Switzerland, several modifications of the tillage parameter file and the crop parameter file were necessary. Examples of our EPIC input and output files can be viewed at http://www.iaw.agrl.ethz.ch/~keusch/files.

The Lake Baldegg catchment (Fig. 1) was chosen for our study because data on soil properties were available from a soil erosion risk assessment by Schudel *et al.* (1991). The test site within this catchment is a 100 m ×100 m (1 ha) field with a 10% slope gradient. The soil is classified as Dystric Cambisol (coarse-silty, mixed, mesic Dystric Eutrochrept) (Table 1). The actual site does not exist in reality, however, it represents the typical field size, slope steepness and soil group of the region. A hypothetical site is assumed for the conformity of an uniformly shaped slope, with homogeneous soil and relief conditions, in order to avoid forms of concentrated flow erosion, such that a simple equation for water erosion (the Universal Soil Loss Equation, USLE) could be used. Mean annual rainfall in the study area is 1100 mm with a summer peak and 135 wet days (>1 mm rainfall) per year; mean annual temperature is 8.8°C.

Four different crop rotations, indicated by corn-, cereal-, potato-, and short-term pasture-rotation according to the dominant crop, were simulated in combination with three different cultivation practices (conventional tillage [mouldboard plough], minimal tillage, cover crop over winter). "Minimal tillage" means that ploughing is replaced by disking, and for cereals chiselling is left out. For the third cultivation technique the land is never left fallow over winter. Before the cultivation of corn or of oats (in the cereal rotation), a cover crop was grown. "Minimal tillage" and "cover crop" are considered as low cost and feasible soil conservation practices adapted to the specific situation of the study area. A change to a more sophisticated no-till and mulch-seeding systems would appear to be too expensive and difficult a practice for most local farms in the near future. Fertilizer and lime were applied according to recommendations of the Swiss Department of Agriculture in two different ways: (a) as inorganic commercial fertilizer and (b) as manure. Pest damage

Table 2 Simulated rainfall erosivity and soil erosion rates compared to results from field measurements. The average soil loss for the simulated test site is the mean value for the four crop rotations (conventional tillage).

Investigation area	USLE *R*-factor (N h^{-1})	Average annual soil loss (t ha^{-1})	Maximum annual soil loss (t ha^{-1})
Lake Baldegg catchment (central Swiss Plateau) Simulated test site (100 years)	130	11	60
High Rhine Valley (north western Switzerland)Aegelsee sub-catchment (5 ha) (1975–1987)	90	5–10	41
Napf (Pre-Alps)(1980–1982)	150	–	–

was "technically" avoided by assigning a very high value (1000 mm of rainfall in a month before damage occurs) to EPIC miscellaneous parameter 9. Each of the 26 combinations obtained from the different crop rotations, cultivation techniques and fertilizer types were run for six different initial total soil profile depths (A- and B-horizon) ranging from 1.2 to 0.45 m, adding up to 156 different runs in total.

RESULTS

Rainfall erosivity

All long-term simulations are based on identical sequences of weather patterns created by the EPIC weather generator. Average monthly precipitation and average number of days of rain per month are drawn from the recorded data (1901–1960) of the nearby meteorological station at Beromünster. The required daily weather generation parameters were calculated with the WXPARM subroutine, supplied by EPIC.

The results of soil erosion field measurements in different parts of Switzerland (compiled in Schaub & Prasuhn, 1991) were used to verify the simulated annual erosion rates (Table 2). The initial runs with EPIC produced comparable observed and synthesized average monthly amounts of rainfall, but considerable overestimations of rainfall erosivity lead to exaggerated soil erosion rates. This is in contradiction with an application of EPIC to the UK South Downs, where the simulated erosivity was lower than expected (Favis-Mortlock, 1995). In this region, however, prolonged low-intensity rainfalls prevail, causing erosion damage after wet antecedent conditions when cover on winter cereal fields is sparse. In the Swiss Plateau intensive storms are more frequent, together with a higher annual amount of rainfall. The EPIC model seems to accentuate these different climatic characteristics. Thus, even for temperate European conditions, model experience cannot be directly transferred from one region to another.

Erosion rates

Reprocessing monthly standard deviations and monthly skew coefficients for daily precipitation using our own statistical routine on observed data for Beromünster (1980–1990) yielded smaller values for these measures of variation, and thus a smaller number of extreme single rainstorms. Therefore, the results for rainfall erosivity and erosion rates were more plausible (Table 2). In the main agricultural region of the Swiss Plateau erosivity increases generally from west to east with higher rainfall due to increasing altitude towards the Pre-Alps, which is consistent with the simulated intermediate value for central Switzerland. The erodibility of the silt-rich soils at the simulated test site is comparable to that of the loess soils in the High Rhine Valley. Considering the higher rainfall erosivity for the Lake Baldegg catchment, simulated and measured average annual erosion rates and maximum annual soil losses correspond quite well.

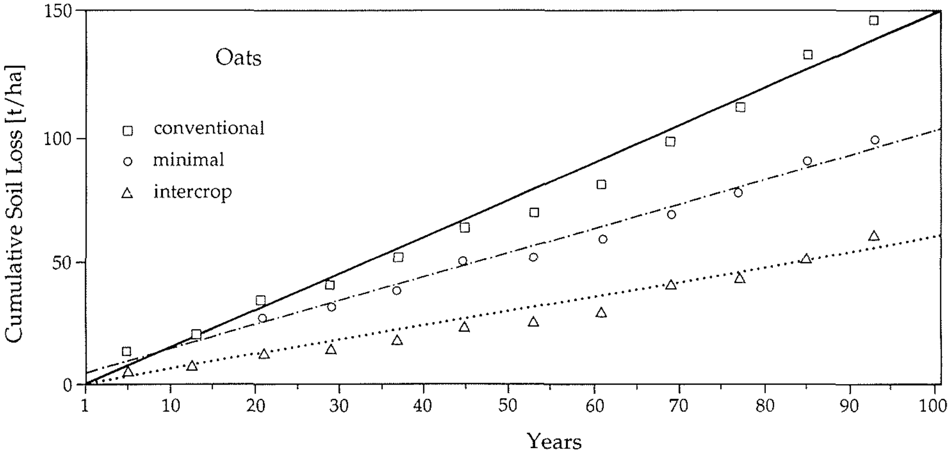

Fig. 2 Cumulative soil losses for oats within the 100 years cereal-rotation (initial soil depth: 1.2 m).

Changes in profile depth and crop yields

The crop yields simulated by EPIC for corn and cereals using the original crop parameter values were reasonable, though at the lower end of the range of measured crop yields in Switzerland. The simulation of potatoes and short-term pasture presented greater difficulty, requiring some parameter adjustments. For this first part of our study however, the relative changes of crop yields as a function of soil depth were of more importance than the absolute values. Differences in fertilizer types and tillage regimes did not significantly influence crop yields.

An example of the simulated crop-specific soil losses over 100 years and the effects of the different cultivation techniques is depicted in Fig. 2. Variability of annual erosion rates is associated with individual weather conditions but overall, the

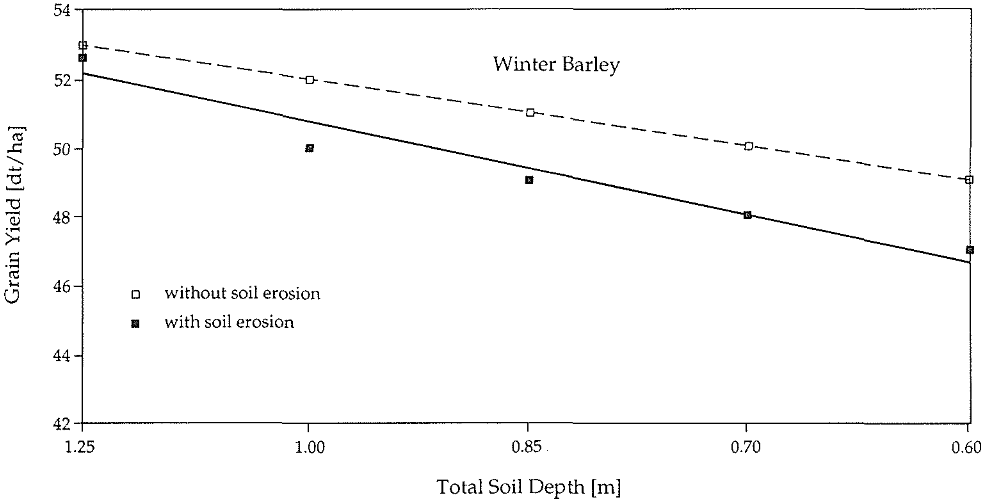

Fig. 3 Simulated barley yield as a function of initial profile depth for 100 years of generated weather.

Table 3 Regression models (polynomial functions) for ten of the 26 cropping treatments (inorganic fertilizer) relating grain yield (dt ha^{-1}) and soil loss (t ha^{-1}) to total soil depth.

Crop and	Yield function					Soil loss function				
tillage	const.	lin.	quadr	t-sign	r^2	const	lin.	quadr	t-sign	r^2
Corn										
conventional	29.67	82.36	-38.92	0.005	0.9986	27.37	-8.45	3.30	0.025	0.973
minimal	31.28	79.56	-7.68	0.005	0.9956	27.26	-9.37	3.69	0.05	0.973
intercrop	36.89	65.98	-30.13	0.005	0.9993	22.66	-8.70	3.68	0.005	0.990
Winter wheat										
conventional	15.59	56.68	-21.98	0.005	0.9999	12.38	-8.16	3.58	0.025	0.987
minimal	16.02	56.44	-22.52	0.005	0.9993	6.92	-3.64	1.59	0.025	0.987
Barley										
conventional	18.91	51.80	-19.54	0.005	0.9992	13.89	-6.62	2.75	0.005	0.997
minimal	19.22	51.22	-19.54	0.005	0.9996	9.35	-5.86	2.61	0.005	0.993
Oats										
conventional	12.25	62.08	-23.68	0.005	0.9989	15.77	-10.42	4.40	0.005	0.994
minimal	15.10	54.55	-19.76	0.005	0.9978	9.08	-5.93	2.50	0.005	0.998
intercrop	15.98	53.40	-20.87	0.005	0.9949	3.55	-1.54	0.55	0.005	0.988

cumulative curves show linear trends for deep soils. A reduction in the initial soil depth caused a linear decrease in average crop yields if soil erosion was suppressed (setting PEC = 0 and ISTA = 1), and an increasing impact on crop yields with soil erosion (Fig. 3). A critical lower limit for the initial soil depth (A- and B-horizon) was found to be around 55 cm.

CONCLUSIONS AND PERSPECTIVES

The EPIC simulations presented in this study successfully reproduced observed erosion rates and crop yields, provided that the daily distributions of the required weather parameters were estimated carefully. The advantages of a model like EPIC is its capability to simulate a large number of long-term scenarios by using synthetic weather which makes it a feasible tool to generate data relevant for an economic decision model with respect to soil management. As an input into the economic model, soil loss and crop yield as a function of the initial soil depth were estimated using regression models (Table 3).

Evaluation of the dynamic economic model, as described by Schmid *et al.* (1998), indicates that on-farm costs due to soil erosion are only of minor significance for the optimal long-term behaviour of the farmer, irrespective of the initial soil depth. Public transfers to farmers (direct payments) are thus justified to increase the relative advantage of environmentally-friendly production methods, provided that society places a high value on the existence of non-eroded soils. The "soil protection index", employed so far, does not seem to be suitable since it is not closely related to a reduction of soil losses. Therefore, more detailed simulations are needed to develop a new soil protection index which adequately reflects the vulnerability of the soil with respect to erosion.

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